Study of the nuclear deformation in relativistic isobar collisions at RHIC

Chunjian Zhang

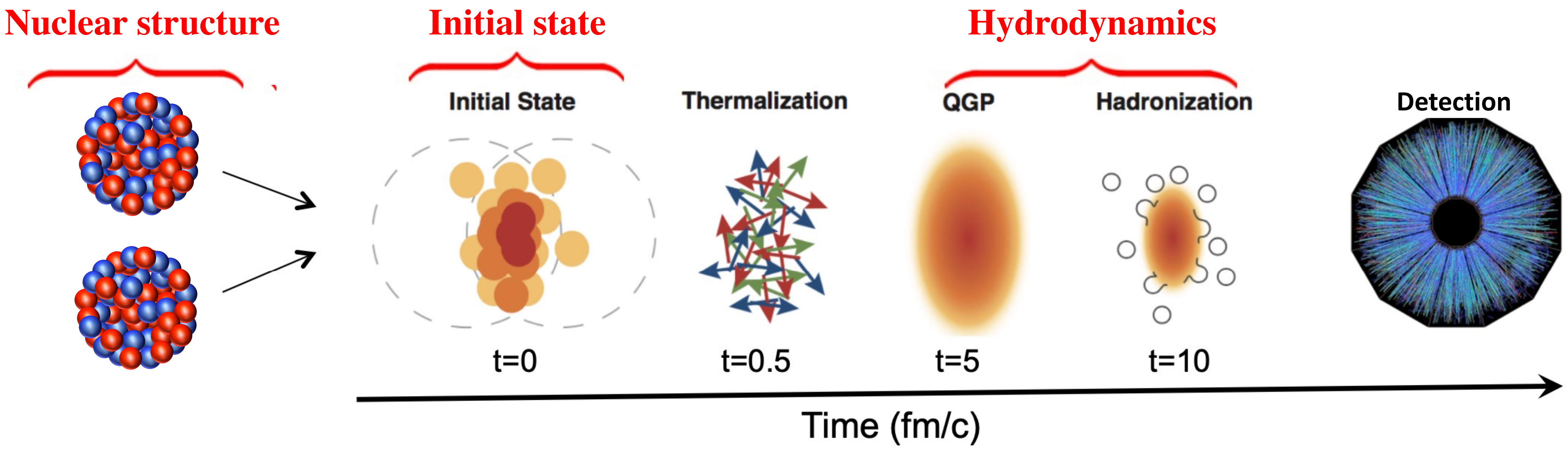
For the STAR Collaboration

Supported by the U.S. DEPARTMENT OF ENERGY Office of Science

Stony Brook University

STAR

Heavy-ion collisions and nuclear structure

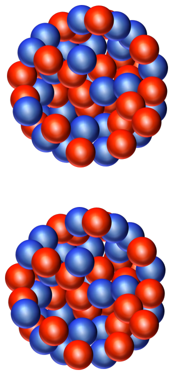


Space-time evolution of heavy-ion collisions can be considered as a hydrodynamic response to the nucleon density distribution in the initial overlap region in the transverse plane, driven by pressure gradient.

The shape and the size of the overlap are controlled by the shape and radial profile of the colliding nuclei.

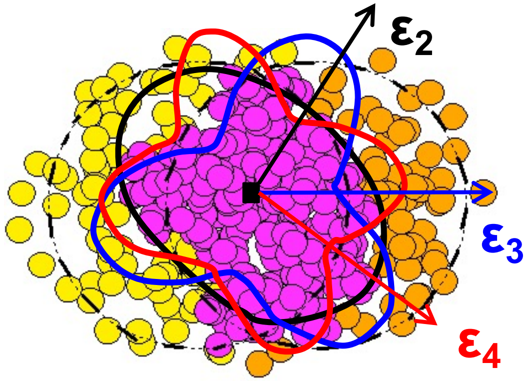
Hydrodynamic response to initial state

Nuclear Structure



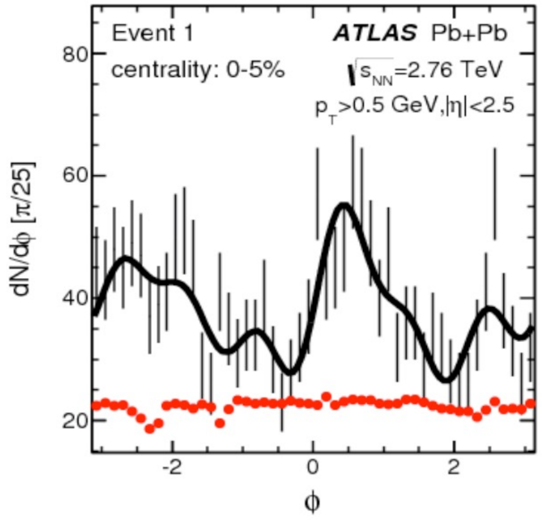
Imaging?

Initial State



hydrodynamic response

Produced Particle Flow



$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{\left(r - R_0\left(1+\sum_n \beta_n Y_n^0(\theta,\phi)\right)\right)/a_0}}$$

Initial Size

$R_\perp^2 \propto \langle r_\perp^2 \rangle$

Initial Shape

$\mathcal{E}_n \propto \langle r_\perp^n e^{in\phi} \rangle$

?

R_0 a_0 β_n

Radial Flow

Anisotropic Flow

$$\frac{d^2N}{d\phi dp_T} = N(p_T)\left(\sum_n V_n e^{-in\phi}\right)$$

$\beta_2 \rightarrow$ Quadrupole deformation

$\beta_3 \rightarrow$ Octupole deformation

$a_0 \rightarrow$ Surface diffuseness

$R_0 \rightarrow$ Nuclear size

D. Teaney et al., arXiv:1206.1905

Approximate linear response in each event:

$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp} \qquad V_n \propto \mathcal{E}_n$$

Connecting shape ε_n and size R to β_n

- ε_n is related to the shape of the Y_n^n projected to the transverse plane

$$\mathcal{E}_n = -\frac{\langle r_\perp^n e^{in\phi}\rangle}{\langle r_\perp^n\rangle} \propto \langle Y_n^n \rangle = \underbrace{\boldsymbol{\epsilon}_{n;0}}_{\text{Undeformed}} + \underbrace{\boldsymbol{p}_n(\Omega_1,\Omega_2)}_{\text{Phase factor}}\beta_n + \mathcal{O}(\beta_n^2)$$

J. Jia, arXiv:2109.00604

Y_n^n: spherical harmonics

$$\boxed{\text{Flow variance } \langle v_n^2\rangle \propto \langle \varepsilon_n^2\rangle = \langle \varepsilon_0^2\rangle + \langle \boldsymbol{p}_2(\Omega_1,\Omega_2)\boldsymbol{p}_2^*(\Omega_1,\Omega_2)\rangle\beta_n^2}$$

- $R_\perp$ is related to Y_2^0 projected to the transverse plane

$$R_\perp^2 = \langle x^2\rangle + \langle y^2\rangle \propto \left\langle 1 - 2\sqrt{\frac{\pi}{5}}Y_2^0\right\rangle$$

$$d_\perp \equiv 1/R_\perp$$

$$\frac{\delta d_\perp}{d_\perp} = \delta_d + p_0(\Omega_1,\Omega_2)\beta_2 + \mathcal{O}(\beta_2^2)$$

fluctuation of δ_d (ϵ_0) is uncorrelated with p_0 $(\boldsymbol{p}_2)$

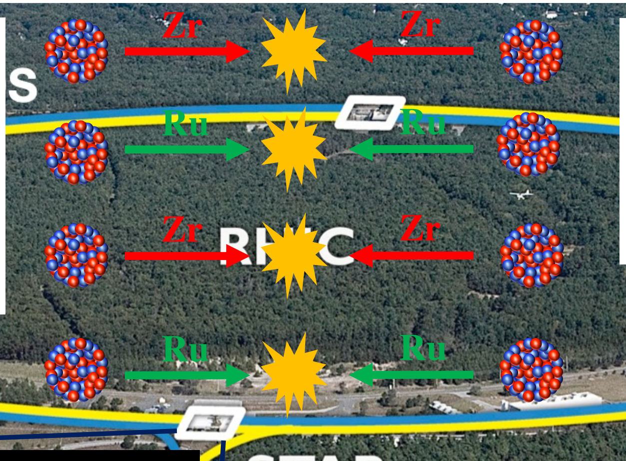
$$\boxed{\text{Variance } \left\langle (\delta[p_T]/[p_T])^2\right\rangle \propto \left\langle (\delta d_\perp/d_\perp)^2\right\rangle = \langle \delta_d^2\rangle + \left\langle p_0(\Omega_1,\Omega_2)^2\right\rangle\beta_2^2}$$

The STAR detector and unique isobar run

1) ${}^{96}_{44}$Ru+${}^{96}_{44}$Ru, ${}^{96}_{40}$Zr+${}^{96}_{40}$Zr at $\sqrt{S_{NN}}$ = 200 GeV

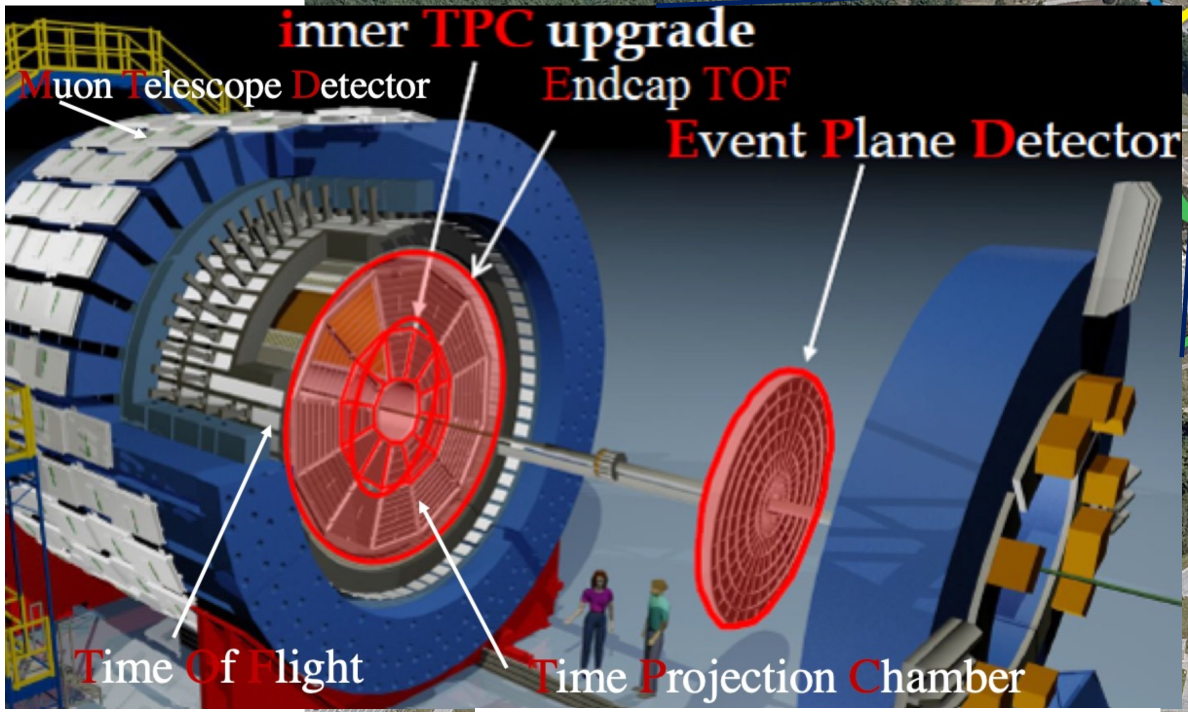
2) Ideal system to study nuclear structure:

$$\frac{v_{n,\mathrm{Ru+Ru}}}{v_{n,\mathrm{Zr+Zr}}} \overset{?}{=} 1$$

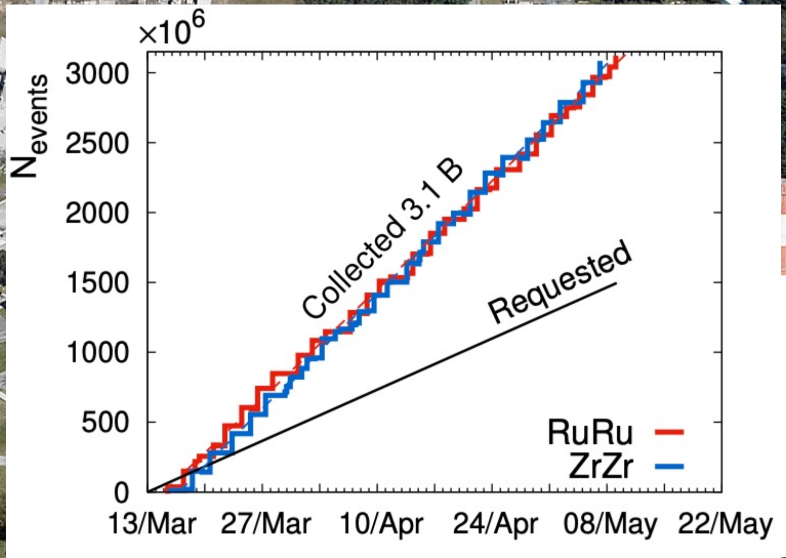


3) Special operation mode:

- Fill-by-fill switching between Ru+Ru and Zr+Zr
- Similar run conditions at STAR (minimize the systematics)



Large, uniform acceptance at mid-rapidity



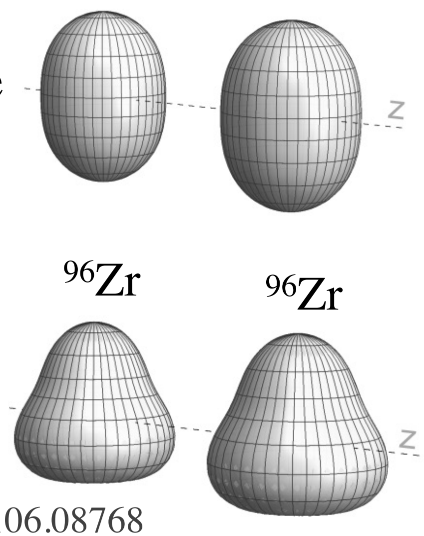
Isobar run originally dedicated to CME search

CME search at RHIC
Session 3 (Nov. 6)
(Fuqiang Wang)

Nuclear deformation in isobar collisions

^{96}Ru ^{96}Ru

Quadrupole



$\beta_2 = 0.162$
$\beta_3 \sim 0$

^{96}Zr ^{96}Zr

Octupole

$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$

J. Jia, aXiv:2106.08768

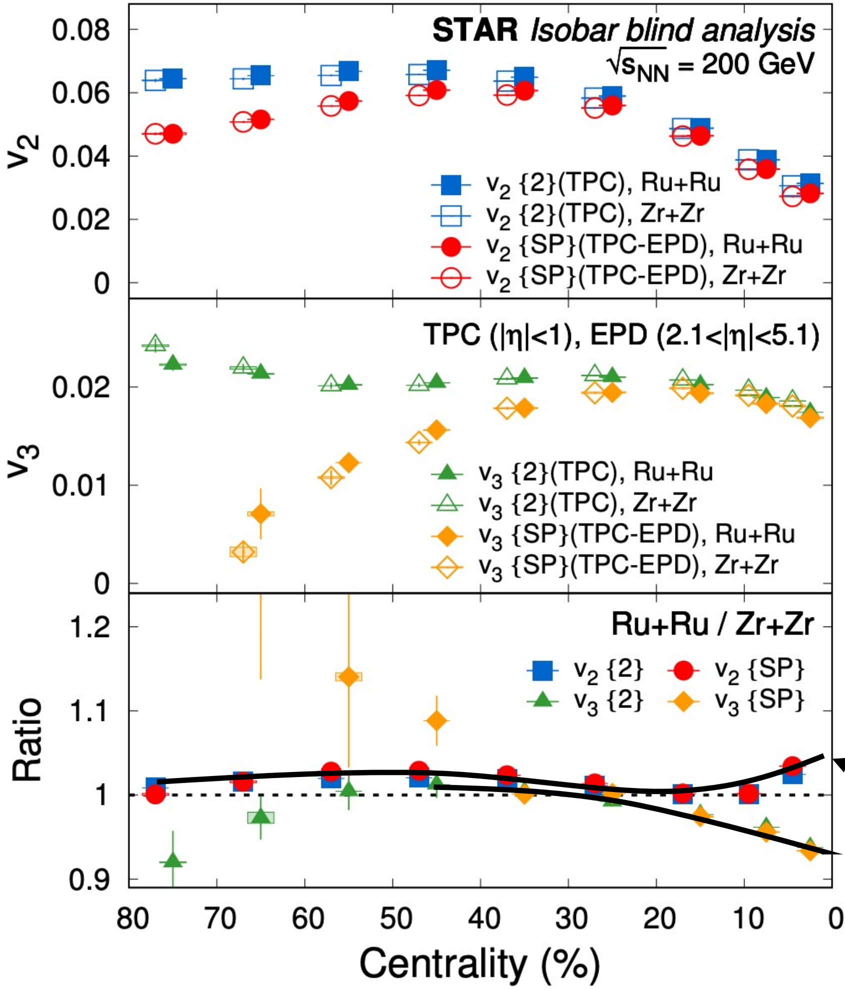
Nuclear structure data on Ru/Zr deformation:

	β_2	$E_{2_1^+}$ (MeV)	β_3	$E_{3_1^-}$ (MeV)
^{96}Ru	0.154	0.83	-	3.08
^{96}Zr	0.062	1.75	0.202,0.235,0.27	1.90

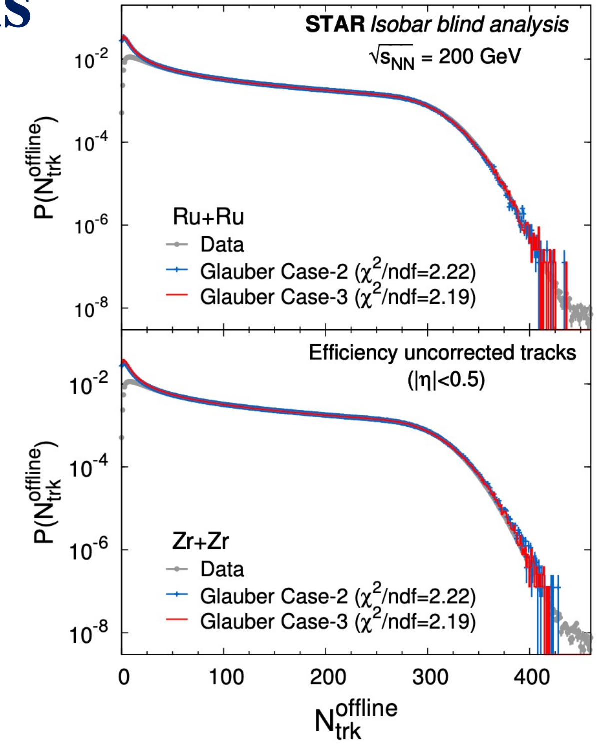
$$\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2)\uparrow}{e^2}} \qquad \beta_3 = \frac{4\pi}{3ZR_0^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$$

C. Zhang et al., arXiv:2109.01631
G. Giacalone et al., arXiv:2102.08158

STAR, arXiv:2109.00131

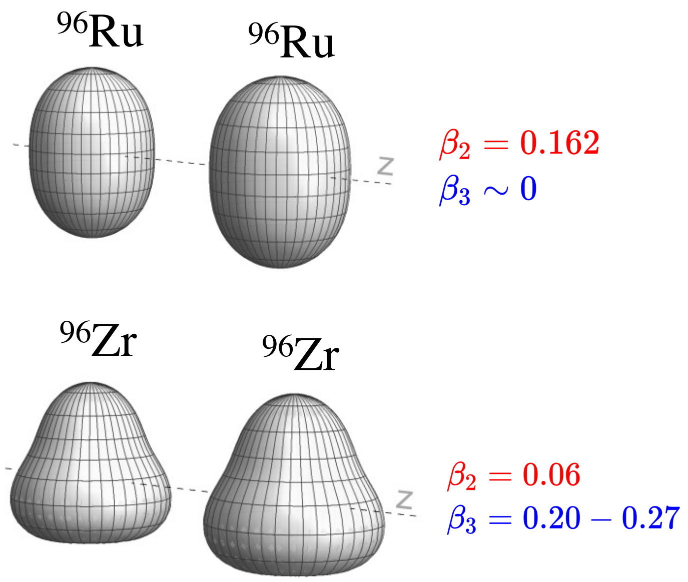


significant departure from One

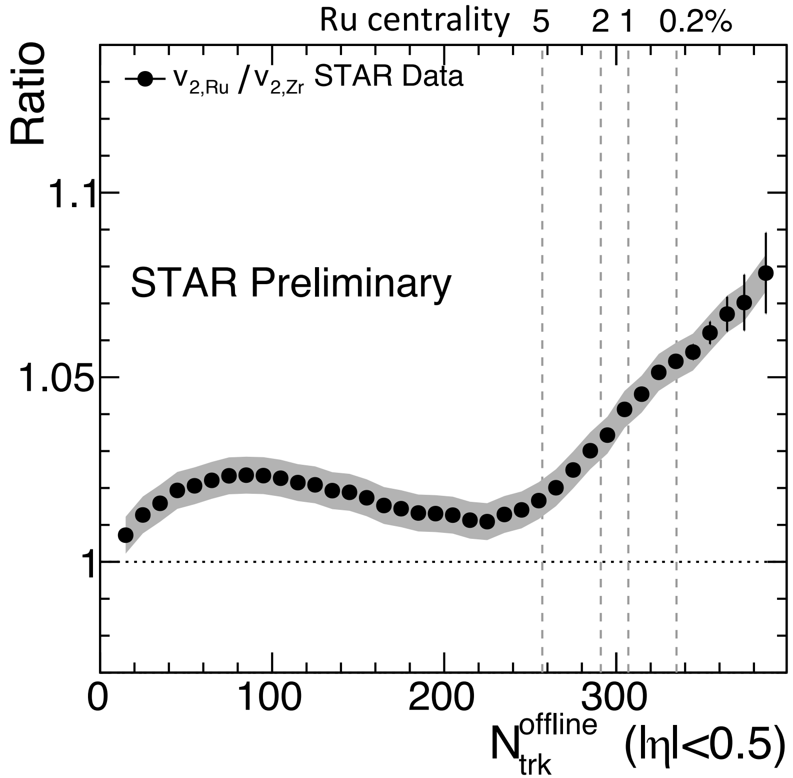


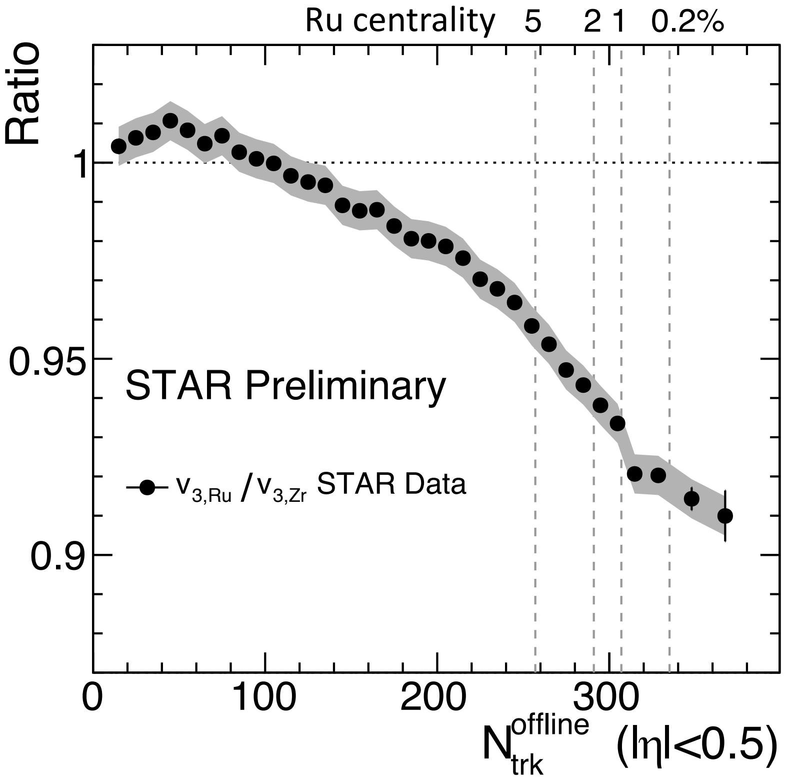
Goal: explore effect of β_n in finer bins of multiplicity

v_2 and v_3 ratio



J. Jia, aXiv:2106.08768





Heavy-ion expectation:

$$v_2^2 = a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2, \quad v_3^2 = a_3 + b_3\beta_3^2$$

$$\frac{v_{2,\mathrm{Ru}}^2}{v_{2,\mathrm{Zr}}^2} \approx 1 + \frac{b_2}{a_2}\left(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2\right) - \underline{\frac{b_{2,3}}{a_2}\beta_{3,\mathrm{Zr}}^2}$$

$$\frac{v_{3,\mathrm{Ru}}^2}{v_{3,\mathrm{Zr}}^2} \approx 1 - \frac{b_3}{a_3}\beta_{3,\mathrm{Zr}}^2 < 1$$

Cancelation expected in non-central collisions

Ratio at same N_{ch} ≠ Ratio at same centrality

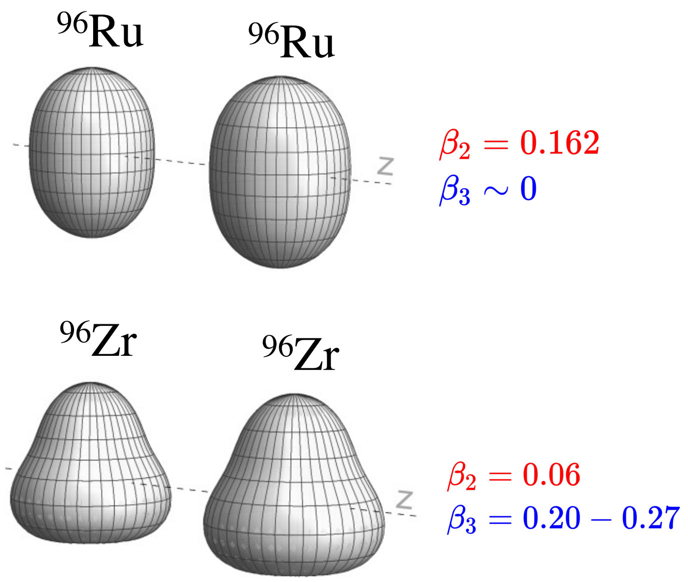
Continuous decrease in v_3 ratio

Nonmonotonic trend in v_2 ratio: enhancement in peripheral and sharp increase in central

✓ The large differences of v_2 and v_3 suggest $\boldsymbol{\beta_{2,\mathrm{Ru}} \gg \beta_{2,\mathrm{Zr}}}$ **and** $\boldsymbol{\beta_{3,\mathrm{Ru}} \ll \beta_{3,\mathrm{Zr}}}$ **.**

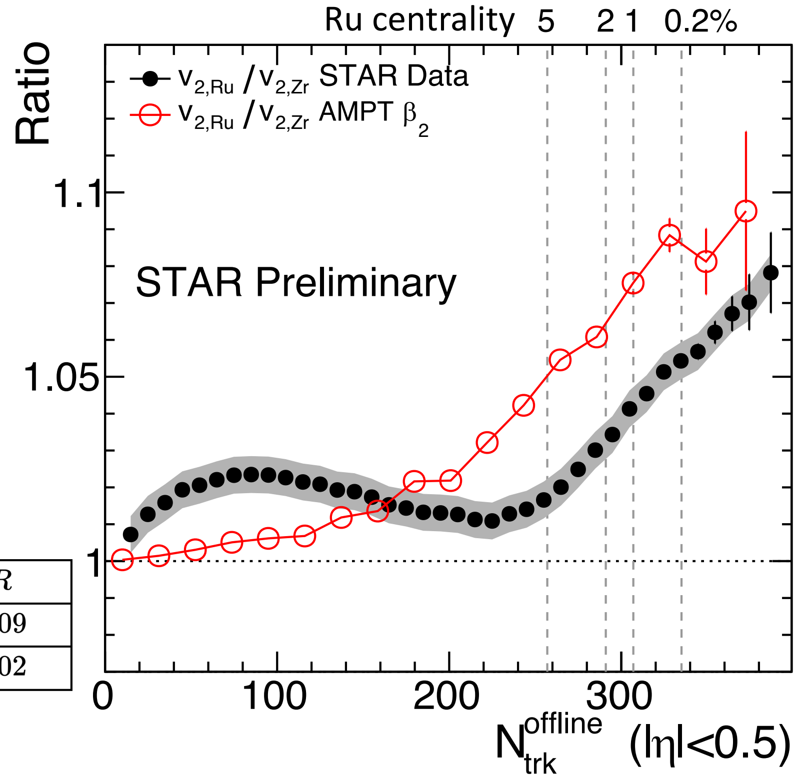
C. Zhang et al., arXiv:2109.01631; G. Giacalone et al., 2105.01638

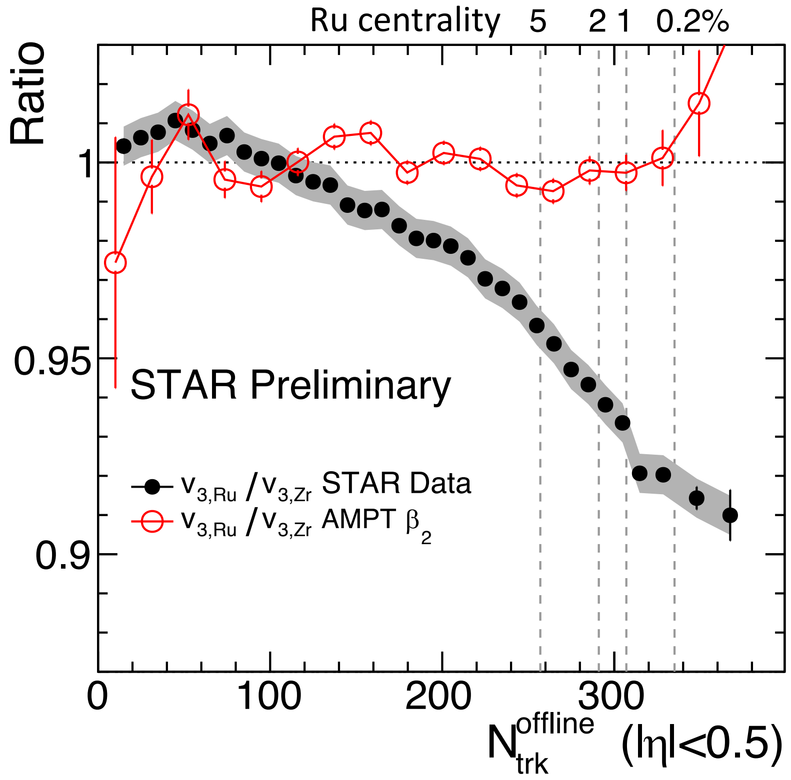
v_2 and v_3 ratio



J. Jia, aXiv:2106.08768

Species	β_2	β_3	a_0	R
Ru+Ru	0.162	0.00	0.46	5.09
Zr+Zr	0.06	0.20	0.52	5.02





v_2 ratio: large increase from $\beta_{2,\mathrm{Ru}}$ in central

v_3 ratio: not affected by $\beta_{2,\mathrm{Ru}}$

Heavy-ion expectation:

$$v_2^2 = a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2, \quad v_3^2 = a_3 + b_3\beta_3^2$$

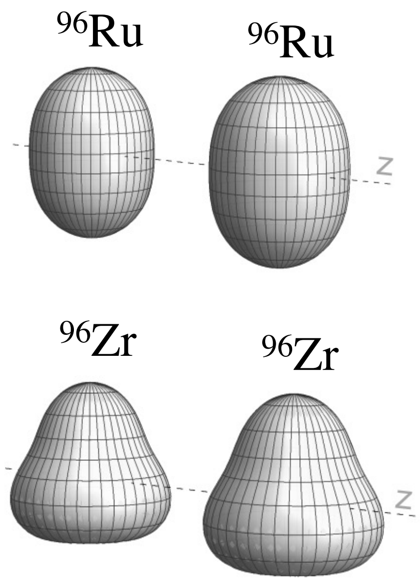
$$\frac{v_{2,\mathrm{Ru}}^2}{v_{2,\mathrm{Zr}}^2} \approx 1 + \frac{b_2}{a_2}\left(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2\right) \underline{- \frac{b_{2,3}}{a_2}\beta_{3,\mathrm{Zr}}^2}$$

$$\frac{v_{3,\mathrm{Ru}}^2}{v_{3,\mathrm{Zr}}^2} \approx 1 - \frac{b_3}{a_3}\beta_{3,\mathrm{Zr}}^2 < 1$$

Cancelation expected in non-central collisions

C. Zhang et al., arXiv:2109.01631; G. Giacalone et al., 2105.01638

v_2 and v_3 ratio

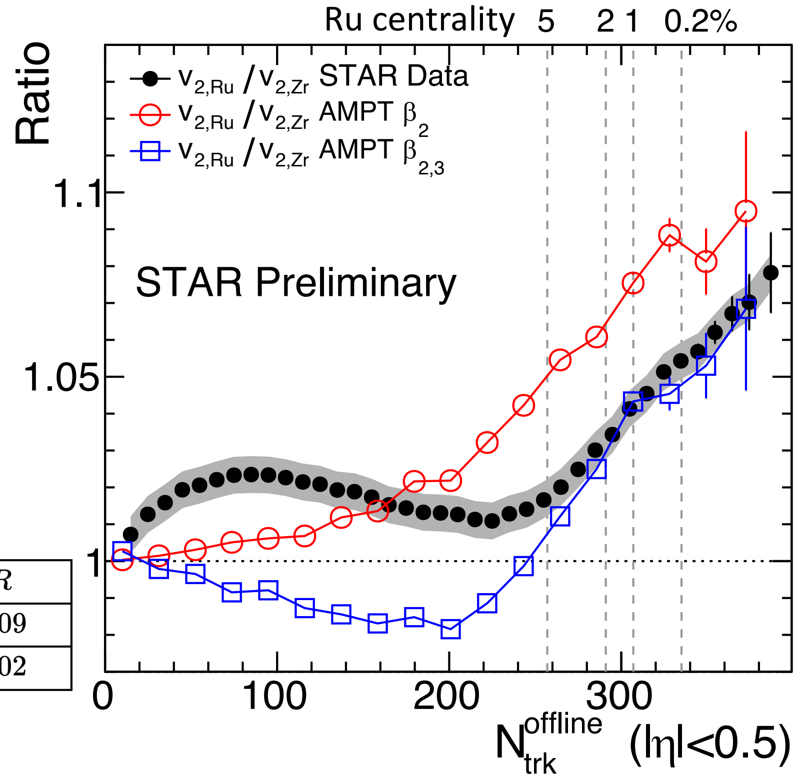


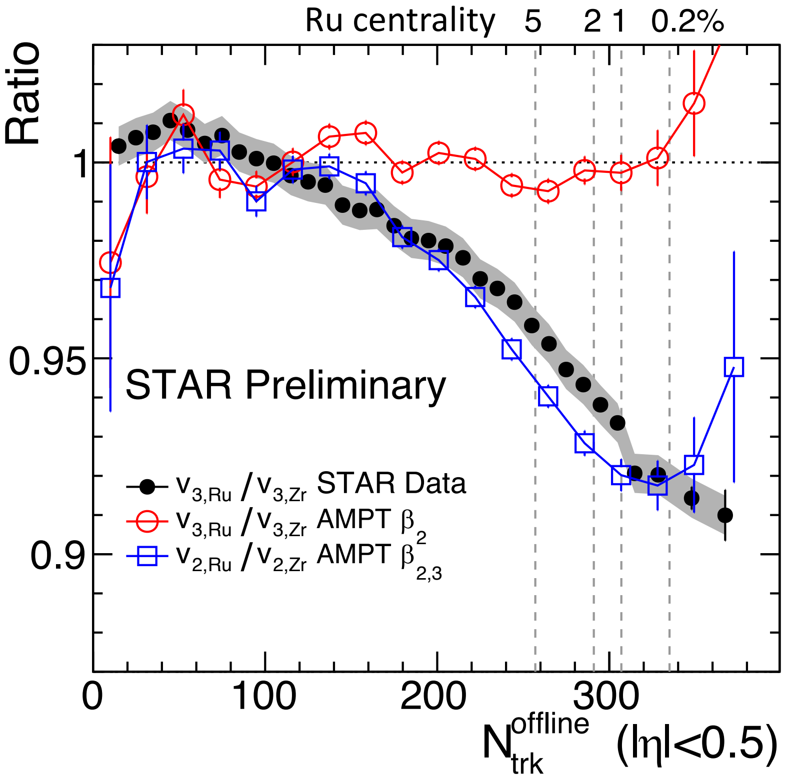
$\beta_2 = 0.162$
$\beta_3 \sim 0$

$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$

J. Jia, aXiv:2106.08768

Species	β_2	β_3	a_0	R
Ru+Ru	0.162	0.00	0.46	5.09
Zr+Zr	0.06	0.20	0.52	5.02





Heavy-ion expectation:

$$v_2^2 = a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2, \quad v_3^2 = a_3 + b_3\beta_3^2$$

$$\frac{v_{2,\mathrm{Ru}}^2}{v_{2,\mathrm{Zr}}^2} \approx 1 + \frac{b_2}{a_2}\left(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2\right) - \underline{\frac{b_{2,3}}{a_2}\beta_{3,\mathrm{Zr}}^2}$$

$$\frac{v_{3,\mathrm{Ru}}^2}{v_{3,\mathrm{Zr}}^2} \approx 1 - \frac{b_3}{a_3}\beta_{3,\mathrm{Zr}}^2 < 1$$

Cancelation expected in non-central collisions

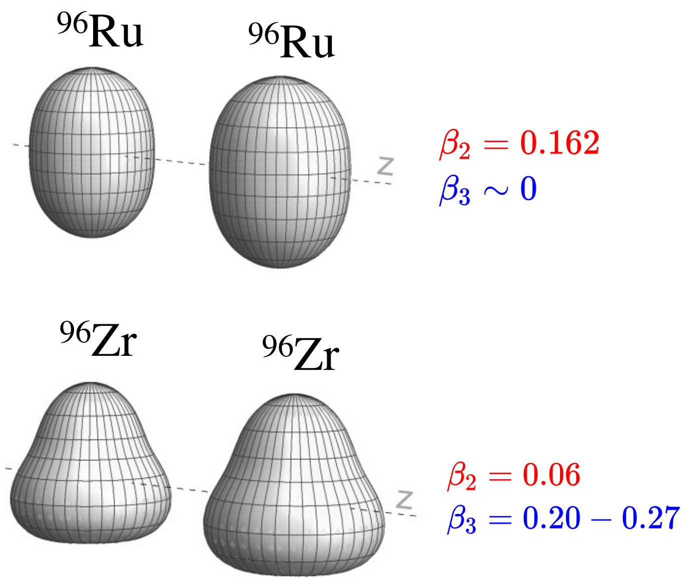
1) v_2 ratio: large $\beta_{2,\mathrm{Ru}}$, negative contribution from $\beta_{3,\mathrm{Zr}}$ ⇒ Sharper increase in central

2) v_3 ratio: strong decrease from $\beta_{3,\mathrm{Zr}}$ with negligible $\beta_{2,\mathrm{Ru}}$ distortion

✓ The large differences of v_2 and v_3 suggest $\boldsymbol{\beta_{2,\mathrm{Ru}} \gg \beta_{2,\mathrm{Zr}}}$ **and** $\boldsymbol{\beta_{3,\mathrm{Ru}} \ll \beta_{3,\mathrm{Zr}}}$.

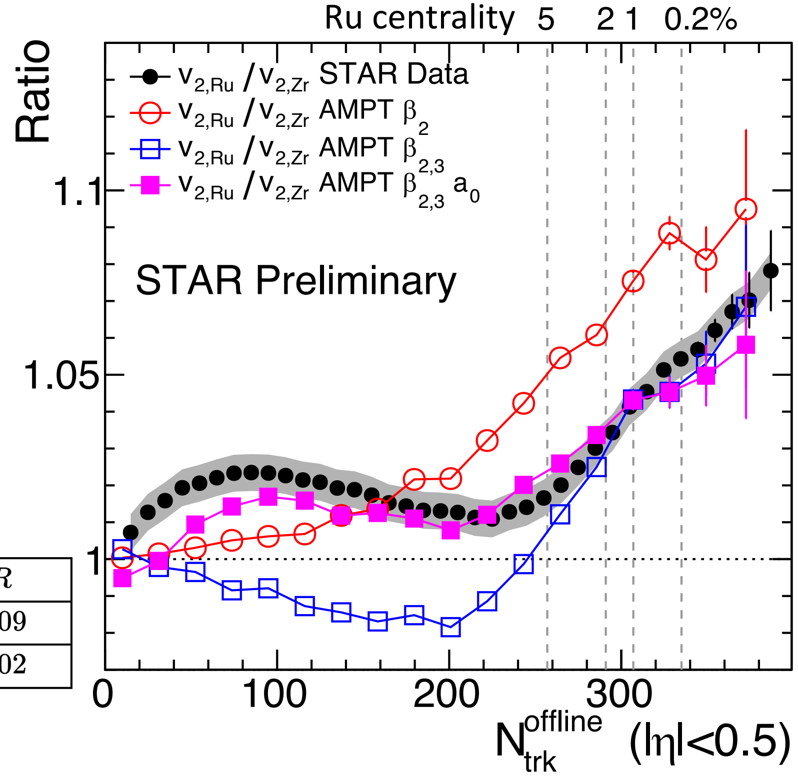
C. Zhang et al., arXiv:2109.01631; G. Giacalone et al., 2105.01638

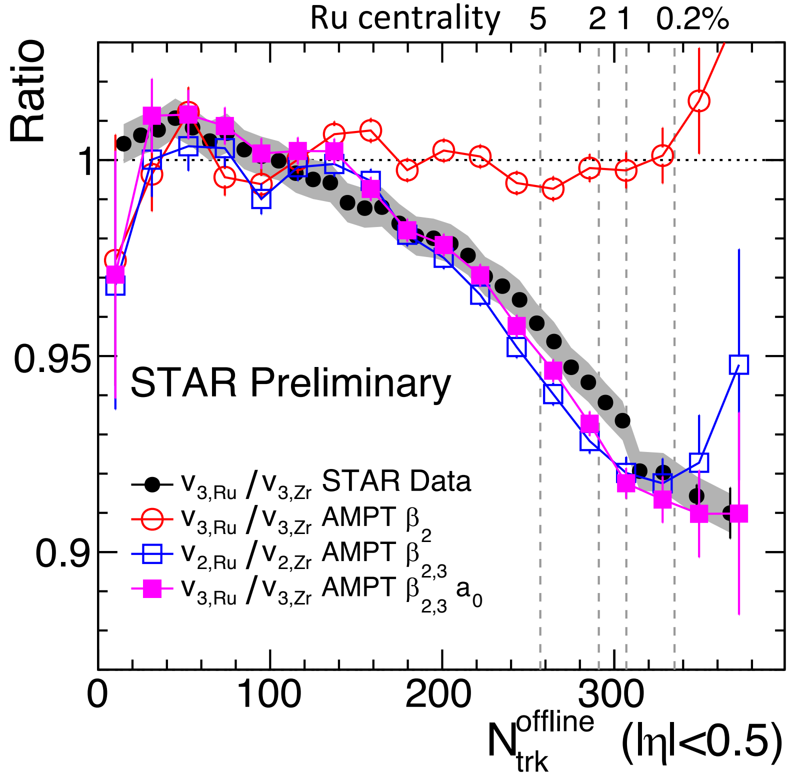
v_2 and v_3 ratio



J. Jia, aXiv:2106.08768

Species	β_2	β_3	a_0	R
Ru+Ru	0.162	0.00	0.46	5.09
Zr+Zr	0.06	0.20	0.52	5.02





Heavy-ion expectation:

$$v_2^2 = a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2, \quad v_3^2 = a_3 + b_3\beta_3^2$$

$$\frac{v_{2,\mathrm{Ru}}^2}{v_{2,\mathrm{Zr}}^2} \approx 1 + \frac{b_2}{a_2}\left(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2\right) - \underline{\frac{b_{2,3}}{a_2}\beta_{3,\mathrm{Zr}}^2}$$

$$\frac{v_{3,\mathrm{Ru}}^2}{v_{3,\mathrm{Zr}}^2} \approx 1 - \frac{b_3}{a_3}\beta_{3,\mathrm{Zr}}^2 < 1$$

Cancelation expected in non-central collisions

1) v_2 ratio: large $\beta_{2,\mathrm{Ru}}$, negative contribution from $\beta_{3,\mathrm{Zr}}$ ⇒ Sharper increase in central

2) v_3 ratio: strong decrease from $\beta_{3,\mathrm{Zr}}$ with negligible $\beta_{2,\mathrm{Ru}}$ distortion

3) Residual effect due to radial structure, e.g., neutron skin in Zr

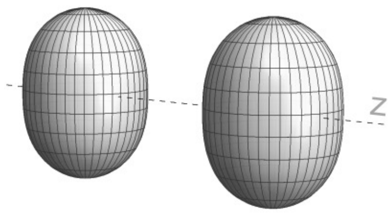
✓ The large differences of v_2 and v_3 suggest $\boldsymbol{\beta_{2,\mathrm{Ru}} \gg \beta_{2,\mathrm{Zr}}}$ **and** $\boldsymbol{\beta_{3,\mathrm{Ru}} \ll \beta_{3,\mathrm{Zr}}}$ **.**

Direct indication of octupole deformation in heavy-ion collisions.

C. Zhang et al., arXiv:2109.01631; G. Giacalone et al., 2105.01638
H. Xu et al., arXiv:1808.06711, 2103.05595, 1910.06170
Q. Shou et al., arXiv:1409.8375

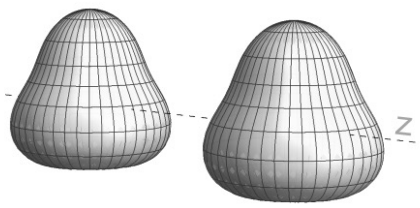
v_2 and v_3 ratio

^{96}Ru ^{96}Ru



$\beta_2 = 0.162$
$\beta_3 \sim 0$

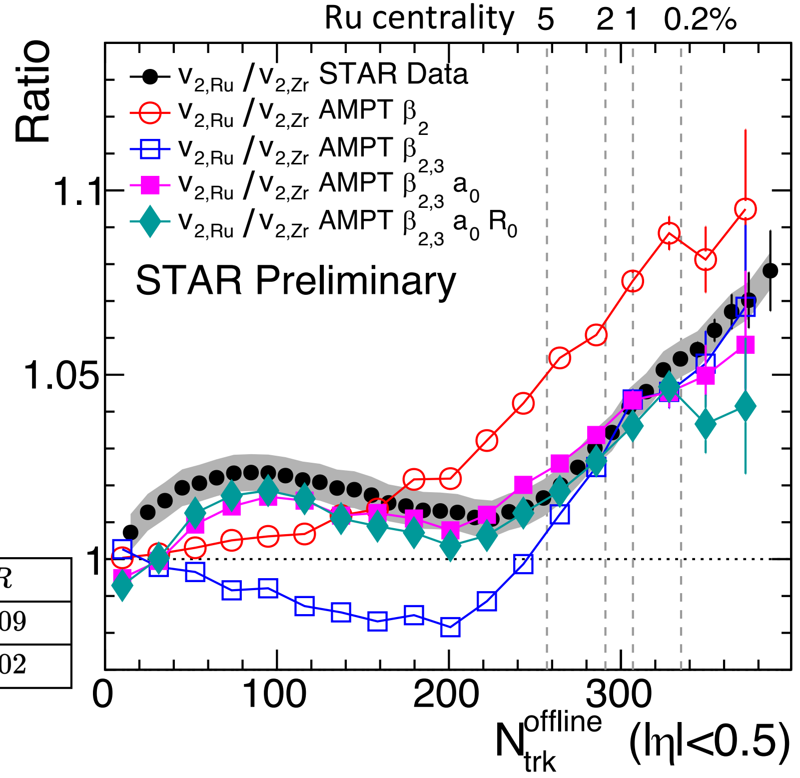
^{96}Zr ^{96}Zr

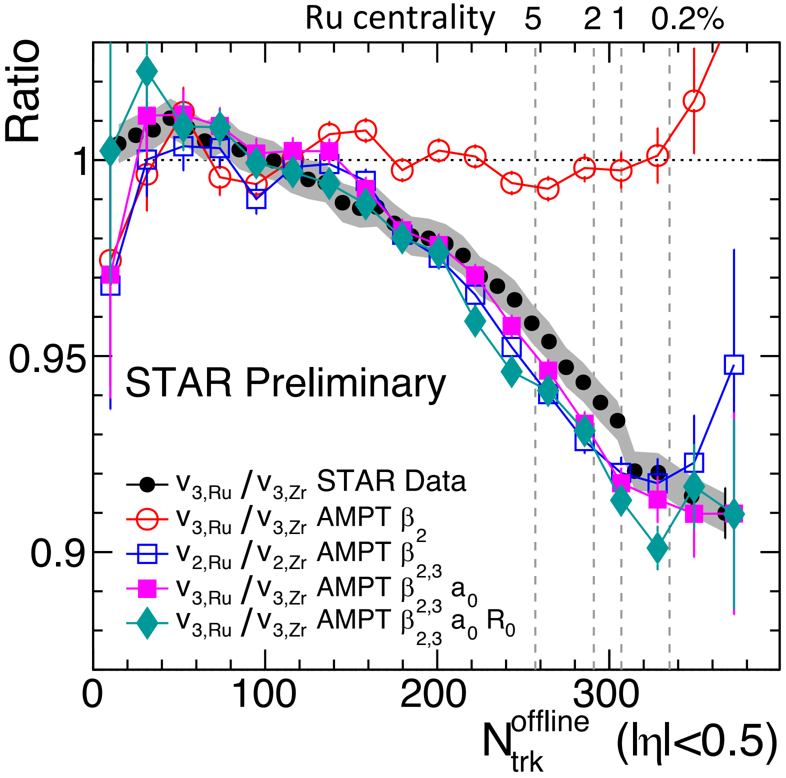


$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$

J. Jia, aXiv:2106.08768

Species	β_2	β_3	a_0	R
Ru+Ru	0.162	0.00	0.46	5.09
Zr+Zr	0.06	0.20	0.52	5.02





Heavy-ion expectation:

$$v_2^2 = a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2, \quad v_3^2 = a_3 + b_3\beta_3^2$$

$$\frac{v_{2,\mathrm{Ru}}^2}{v_{2,\mathrm{Zr}}^2} \approx 1 + \frac{b_2}{a_2}\left(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2\right) \underline{- \frac{b_{2,3}}{a_2}\beta_{3,\mathrm{Zr}}^2}$$

$$\frac{v_{3,\mathrm{Ru}}^2}{v_{3,\mathrm{Zr}}^2} \approx 1 - \frac{b_3}{a_3}\beta_{3,\mathrm{Zr}}^2 < 1$$

Cancelation expected in non-central collisions

1) v_2 ratio: large $\beta_{2,\mathrm{Ru}}$, negative contribution from $\beta_{3,\mathrm{Zr}}$ ⇒ Sharper increase in central

2) v_3 ratio: strong decrease from $\beta_{3,\mathrm{Zr}}$ with negligible $\beta_{2,\mathrm{Ru}}$ distortion

3) Residual effect due to radial structure, e.g., neutron skin in Zr

4) No significant effect due to nuclear size

✓ The large differences of v_2 and v_3 suggest $\boldsymbol{\beta_{2,\mathrm{Ru}} \gg \beta_{2,\mathrm{Zr}}}$ **and** $\boldsymbol{\beta_{3,\mathrm{Ru}} \ll \beta_{3,\mathrm{Zr}}}$.

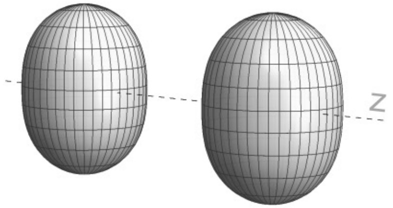
Direct indication of octupole deformation in heavy-ion collisions.

C. Zhang et al., arXiv:2109.01631; G. Giacalone et al., 2105.01638
H. Xu et al., arXiv:1808.06711, 2103.05595, 1910.06170
Q. Shou et al., arXiv:1409.8375

$[p_T]$-variance ratio

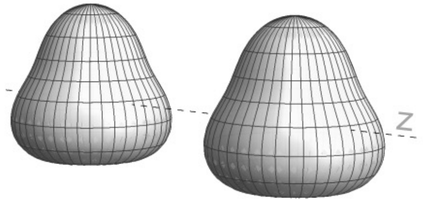
J. Jia, aXiv:2106.08768

^{96}Ru ^{96}Ru



$\beta_2 = 0.162$
$\beta_3 \sim 0$

^{96}Zr ^{96}Zr



$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$

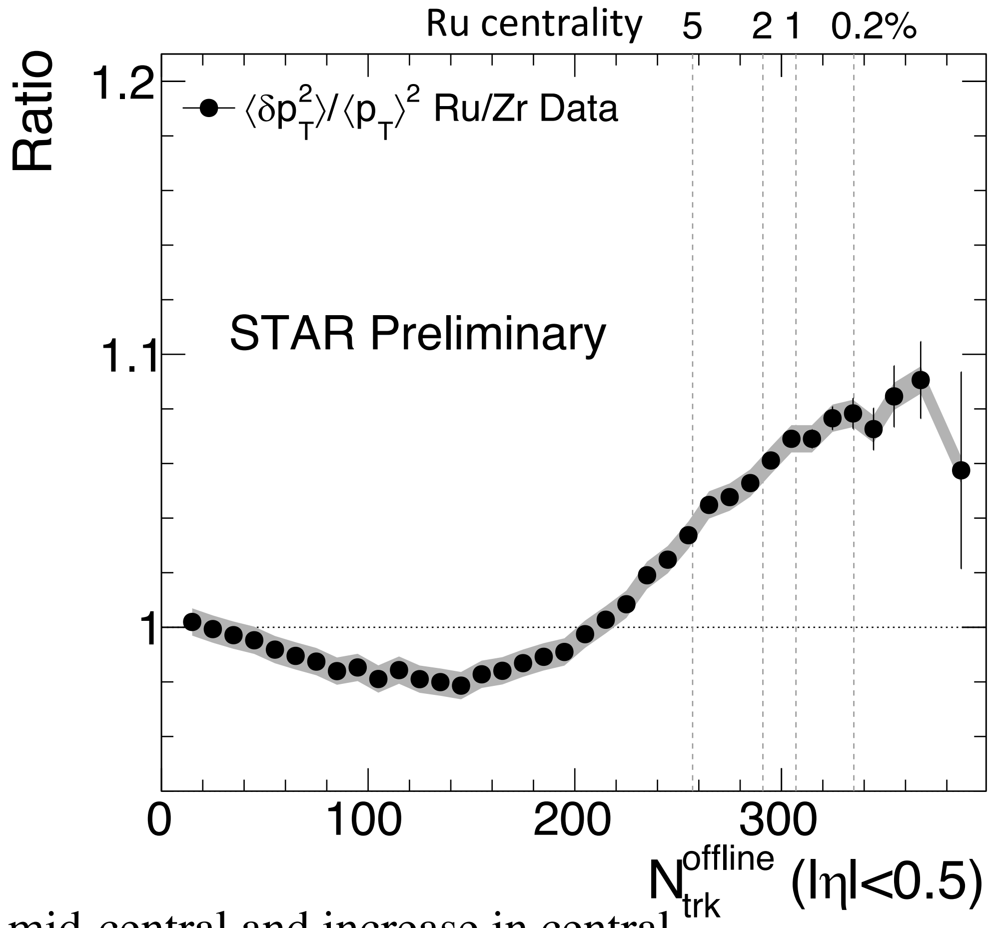
Heavy-ion expectation:

$$\left\langle (\delta[p_{\mathrm{T}}]/[p_{\mathrm{T}}])^2 \right\rangle = a_0 + b_0\beta_2^2 + b_{0,3}\beta_3^2$$

$$\frac{\langle \delta p_T^2 \rangle_{\mathrm{Ru}}}{\langle \delta p_T^2 \rangle_{\mathrm{Zr}}} \approx 1 + \frac{b_0}{a_0}(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2) - \underline{\frac{b_{0,3}}{a_0}\beta_{3,\mathrm{Zr}}^2}$$

Cancelation expected in non-central collisions

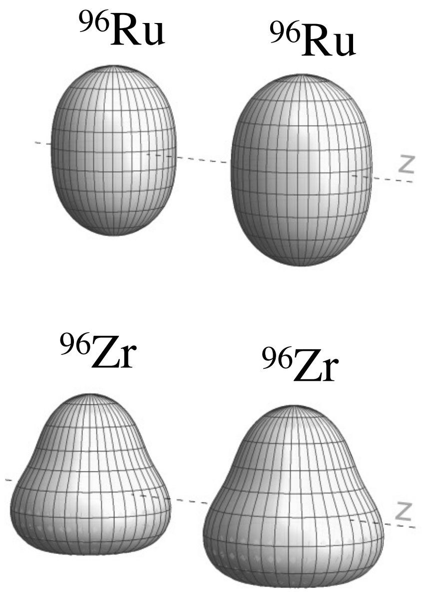
$$\left\langle (\delta[p_{\mathrm{T}}]/[p_{\mathrm{T}}])^2 \right\rangle \propto \left\langle (\delta d_\perp/d_\perp)^2 \right\rangle = \langle \delta_d^2 \rangle + \left\langle p_0(\Omega_1, \Omega_2, \gamma)^2 \right\rangle \beta_2^2$$



1) Nonmonotonic trend: large suppression in mid-central and increase in central

[p_T]-variance ratio

J. Jia, aXiv:2106.08768



$\beta_2 = 0.162$
$\beta_3 \sim 0$

$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$

Heavy-ion expectation:

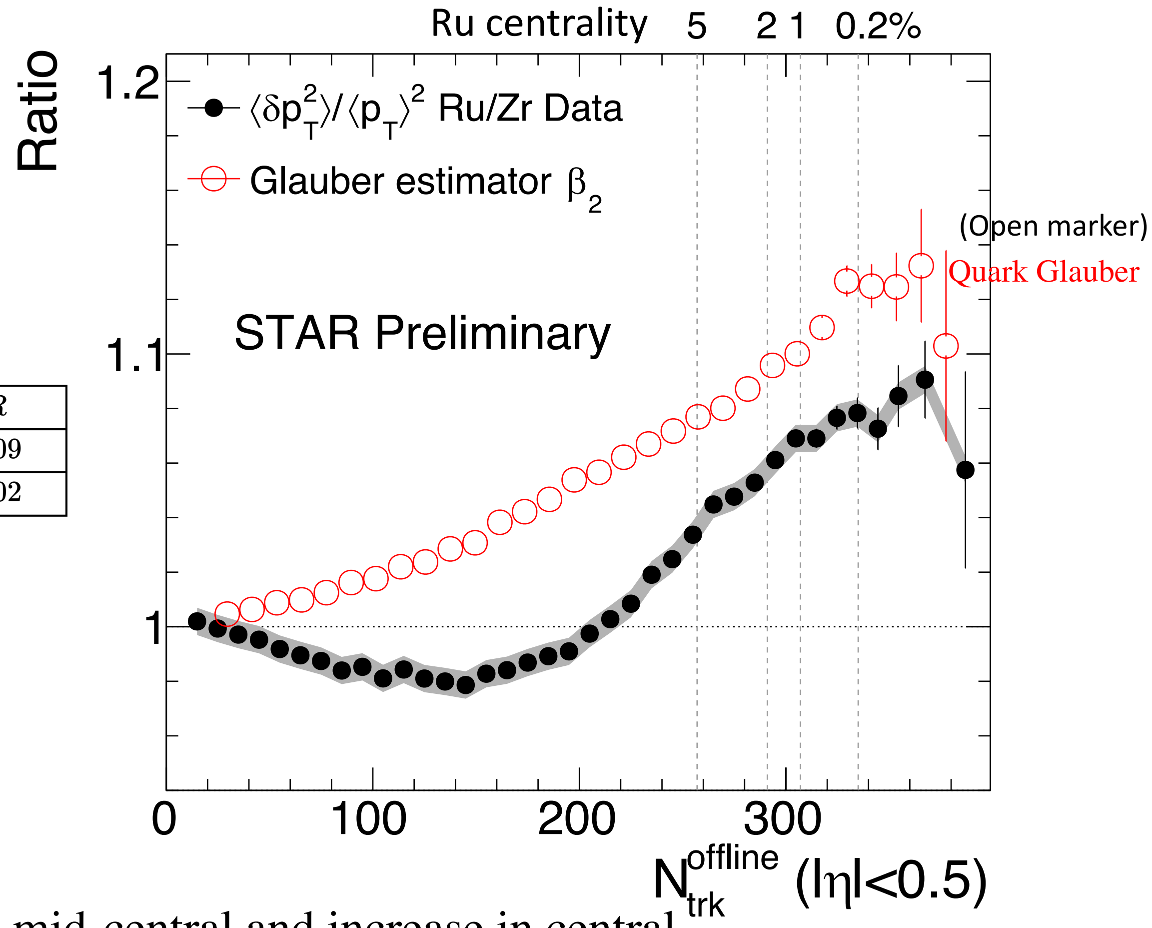
$$\left\langle (\delta[p_{\mathrm{T}}]/[p_{\mathrm{T}}])^2 \right\rangle = a_0 + b_0\beta_2^2 + b_{0,3}\beta_3^2$$

$$\frac{\langle \delta p_T^2 \rangle_{\mathrm{Ru}}}{\langle \delta p_T^2 \rangle_{\mathrm{Zr}}} \approx 1 + \frac{b_0}{a_0}(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2) - \underline{\frac{b_{0,3}}{a_0}\beta_{3,\mathrm{Zr}}^2}$$

Cancelation expected in non-central collisions

Species	β_2	β_3	a_0	R
Ru+Ru	0.162	0.00	0.46	5.09
Zr+Zr	0.06	0.20	0.52	5.02

$$\left\langle (\delta[p_{\mathrm{T}}]/[p_{\mathrm{T}}])^2 \right\rangle \propto \left\langle (\delta d_\perp/d_\perp)^2 \right\rangle = \langle \delta_d^2 \rangle + \left\langle p_0(\Omega_1,\Omega_2,\gamma)^2 \right\rangle \beta_2^2$$

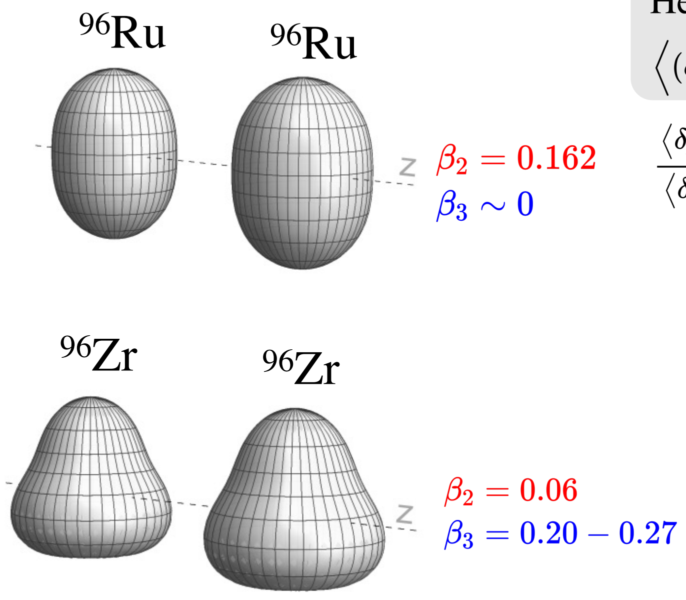


1) Nonmonotonic trend: large suppression in mid-central and increase in central

2) Enhancement from mid-central ⇒ large $\beta_{2,\mathrm{Ru}}$

$[p_T]$-variance ratio

J. Jia, aXiv:2106.08768



Heavy-ion expectation:

$$\left\langle (\delta[p_T]/[p_T])^2 \right\rangle = a_0 + b_0\beta_2^2 + b_{0,3}\beta_3^2$$

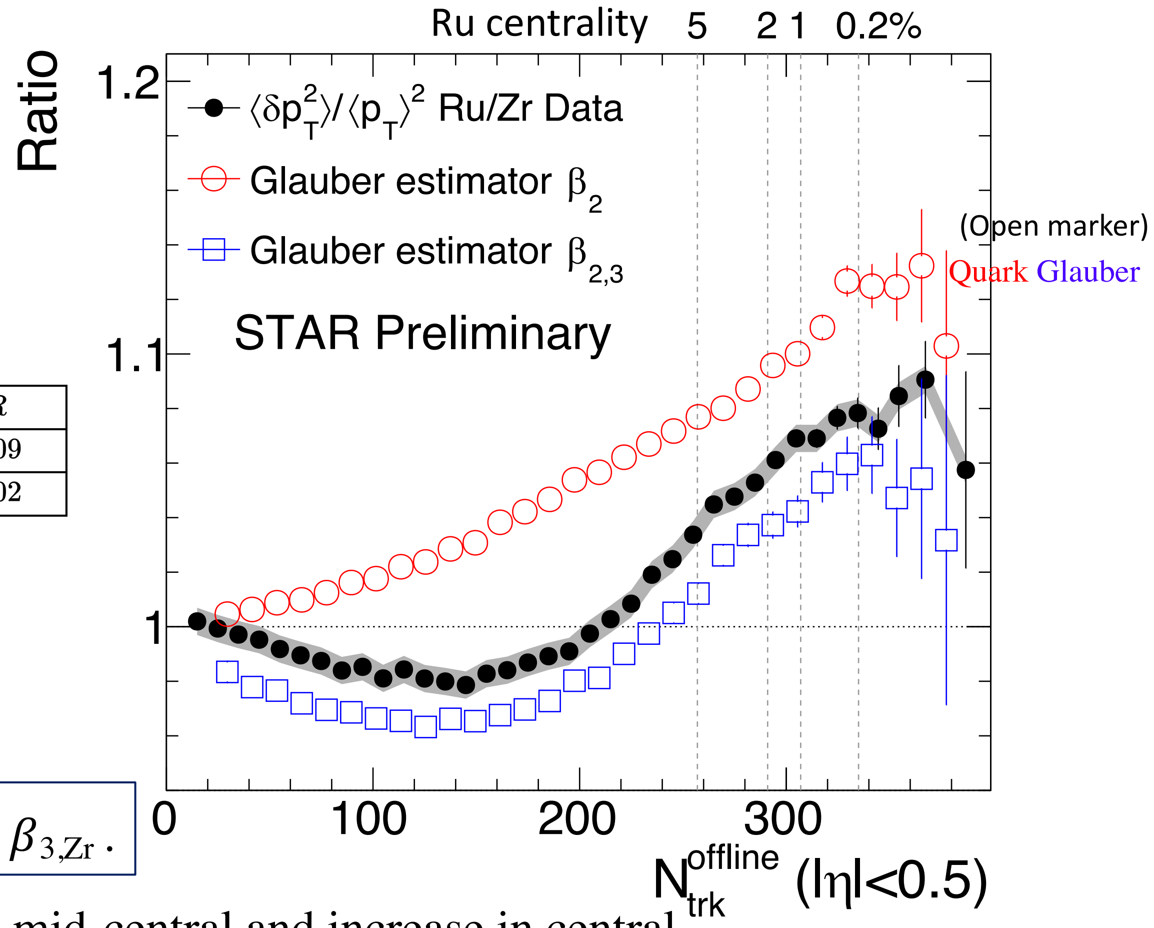
$$\frac{\langle \delta p_T^2 \rangle_{\mathrm{Ru}}}{\langle \delta p_T^2 \rangle_{\mathrm{Zr}}} \approx 1 + \frac{b_0}{a_0}(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2) - \underline{\frac{b_{0,3}}{a_0}\beta_{3,\mathrm{Zr}}^2}$$

Cancelation expected in non-central collisions

Species	β_2	β_3	a_0	R
Ru+Ru	0.162	0.00	0.46	5.09
Zr+Zr	0.06	0.20	0.52	5.02

$$\left\langle (\delta[p_T]/[p_T])^2 \right\rangle \propto \left\langle (\delta d_\perp/d_\perp)^2 \right\rangle = \langle \delta_d^2 \rangle + \left\langle p_0(\Omega_1,\Omega_2,\gamma)^2 \right\rangle \beta_2^2$$

$$\checkmark\ \beta_{2,\mathrm{Ru}} \gg \beta_{2,\mathrm{Zr}} \text{ and } \beta_{3,\mathrm{Ru}} \ll \beta_{3,\mathrm{Zr}}\,.$$



1) Nonmonotonic trend: large suppression in mid-central and increase in central

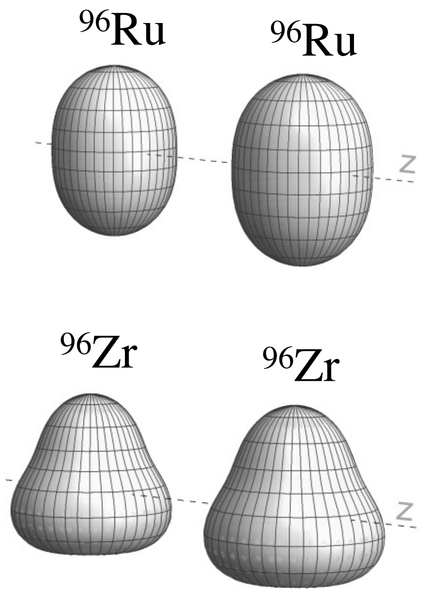
2) Enhancement from mid-central ⇒ large $\beta_{2,\mathrm{Ru}}$

3) Large suppression in mid-central ⇒ strong octupole $\beta_{3,\mathrm{Zr}}$

Variance of $[p_T]$ fluctuations can also be used to constrain the nuclear deformation.

$[p_T]$-variance ratio

J. Jia, aXiv:2106.08768



$\beta_2 = 0.162$
$\beta_3 \sim 0$

$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$

Heavy-ion expectation:

$$\left\langle (\delta[p_T]/[p_T])^2 \right\rangle = a_0 + b_0\beta_2^2 + b_{0,3}\beta_3^2$$

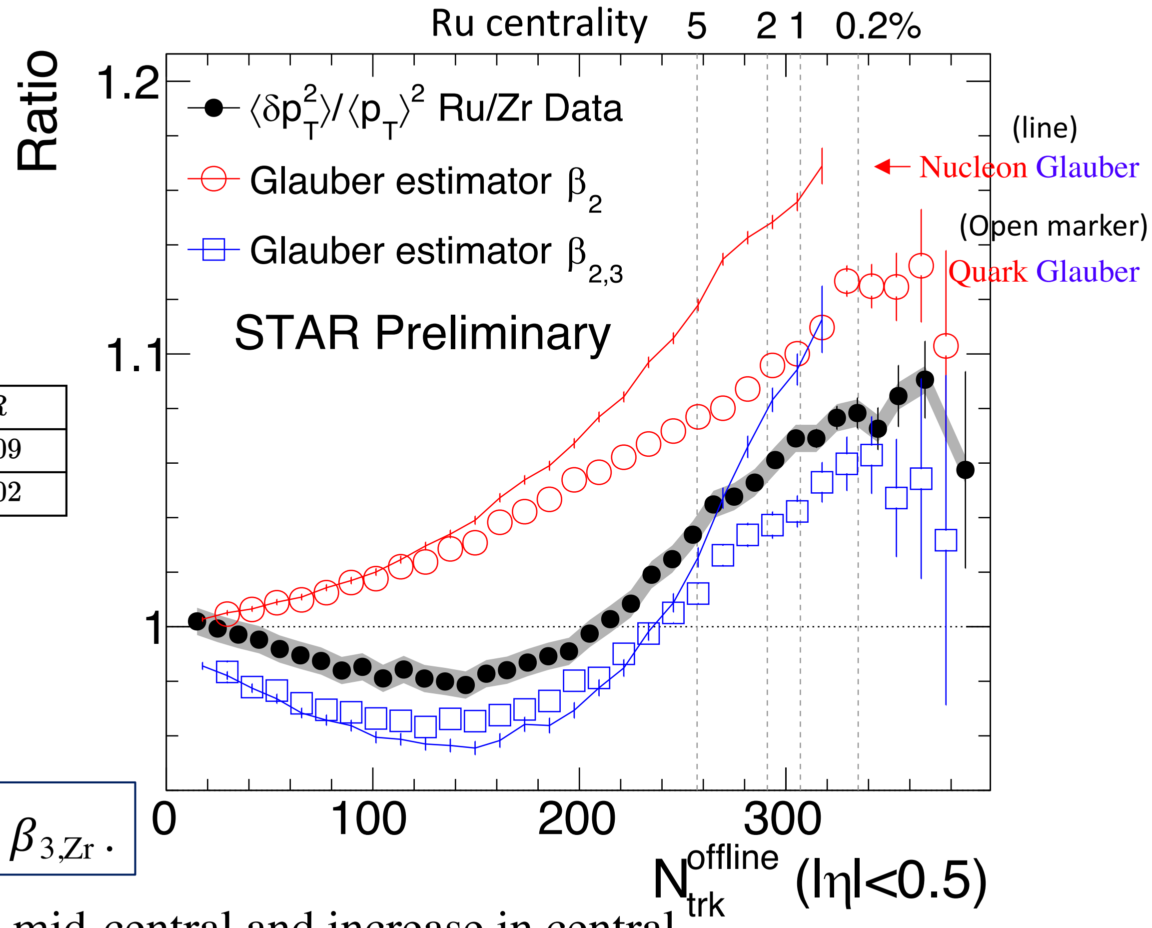
$$\frac{\langle \delta p_T^2 \rangle_{\rm Ru}}{\langle \delta p_T^2 \rangle_{\rm Zr}} \approx 1 + \frac{b_0}{a_0}(\beta_{2,\rm Ru}^2 - \beta_{2,\rm Zr}^2) - \underline{\frac{b_{0,3}}{a_0}\beta_{3,\rm Zr}^2}$$

Cancelation expected in non-central collisions

Species	β_2	β_3	a_0	R
Ru+Ru	0.162	0.00	0.46	5.09
Zr+Zr	0.06	0.20	0.52	5.02

$$\left\langle (\delta[p_T]/[p_T])^2 \right\rangle \propto \left\langle (\delta d_\perp/d_\perp)^2 \right\rangle = \langle \delta_d^2 \rangle + \left\langle p_0(\Omega_1,\Omega_2,\gamma)^2 \right\rangle \beta_2^2$$

✓ $\beta_{2,\rm Ru} \gg \beta_{2,\rm Zr}$ and $\beta_{3,\rm Ru} \ll \beta_{3,\rm Zr}$.



1) <u>Nonmonotonic trend:</u> large suppression in mid-central and increase in central

2) Enhancement from mid-central ⇒ large $\beta_{2,\rm Ru}$

3) Large suppression in mid-central ⇒ strong octupole $\beta_{3,\rm Zr}$

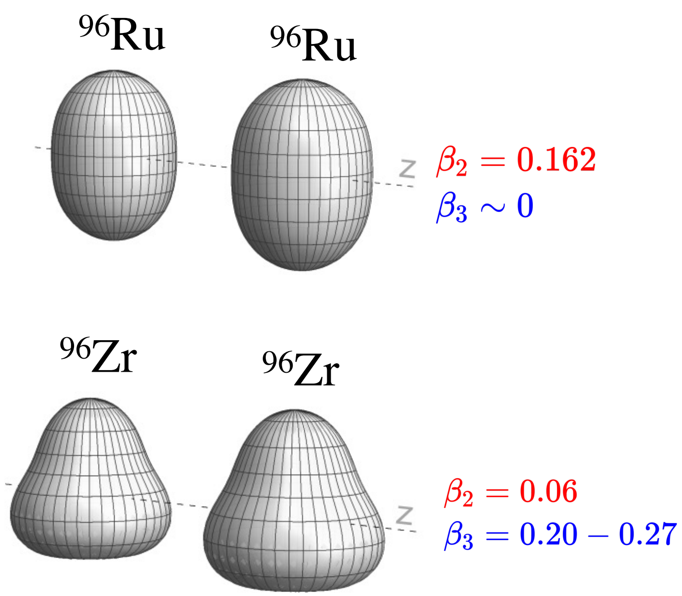
Variance of $[p_T]$ fluctuations can also be used to constrain the nuclear deformation.

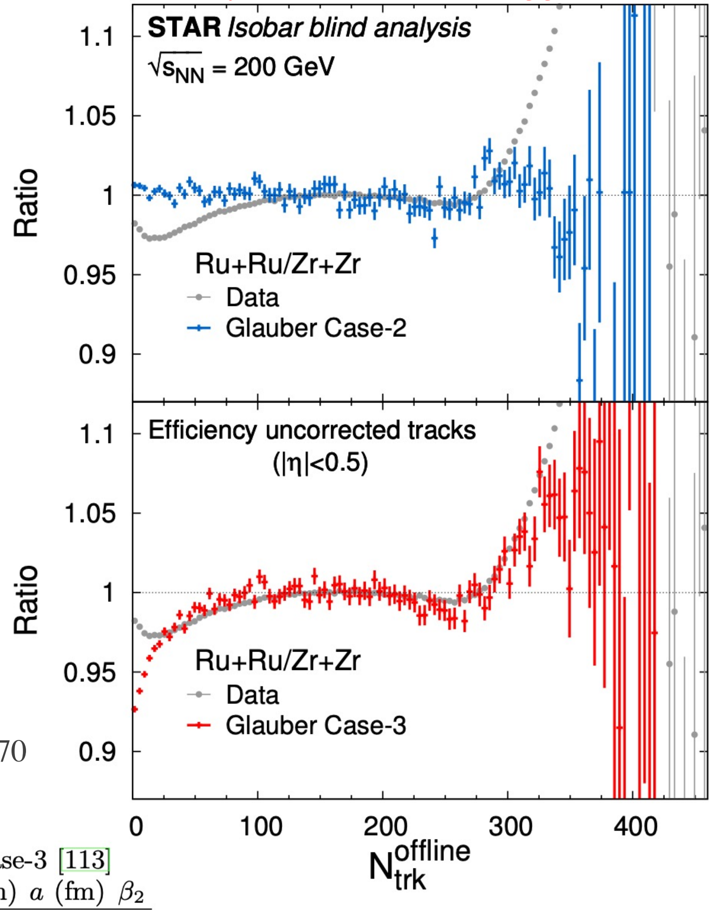
Multiplicity ratio

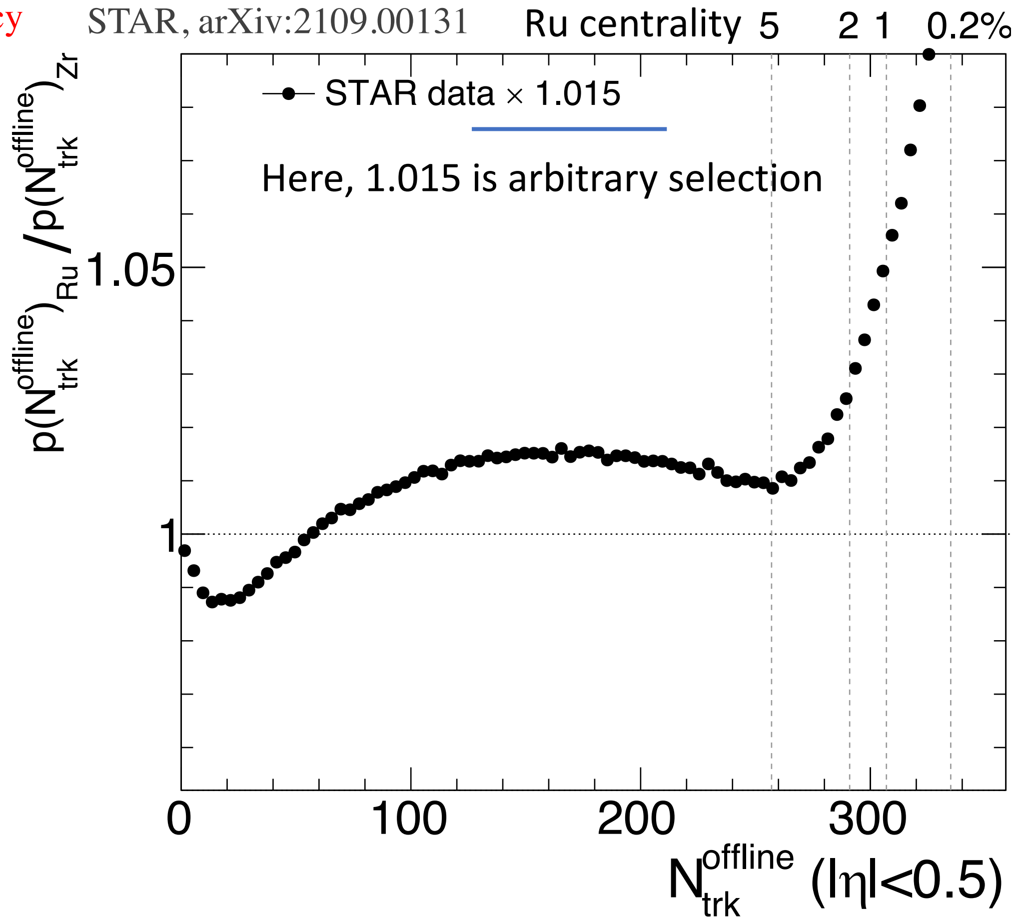
J. Jia, aXiv:2106.08768

! Note the normalization is very sensitive to the trigger efficiency

STAR, arXiv:2109.00131







STAR, arXiv:2109.00131

H. Xu et al., arXiv:1808.06711, 2103.05595, 1910.06170

Q. Shou et al., arXiv:1409.8375

	Case-1 [83]			Case-2 [83]			Case-3 [113]		
Nucleus	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.02	0.46	0.08	5.02	0.46	0.217	4.965	0.556	0

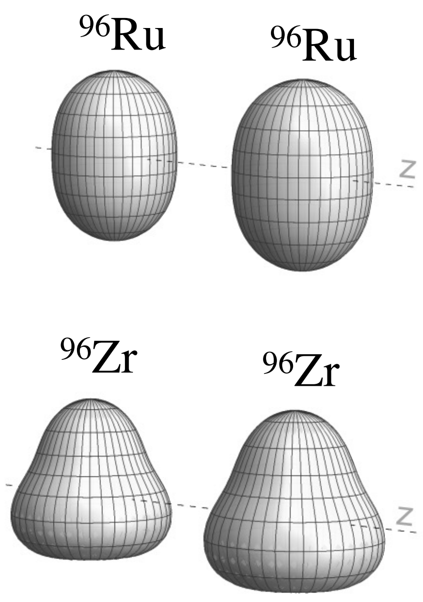
1) Nonmonotonic trend: bump in mid-central and increase in central

Multiplicity ratio

J. Jia, aXiv:2106.08768

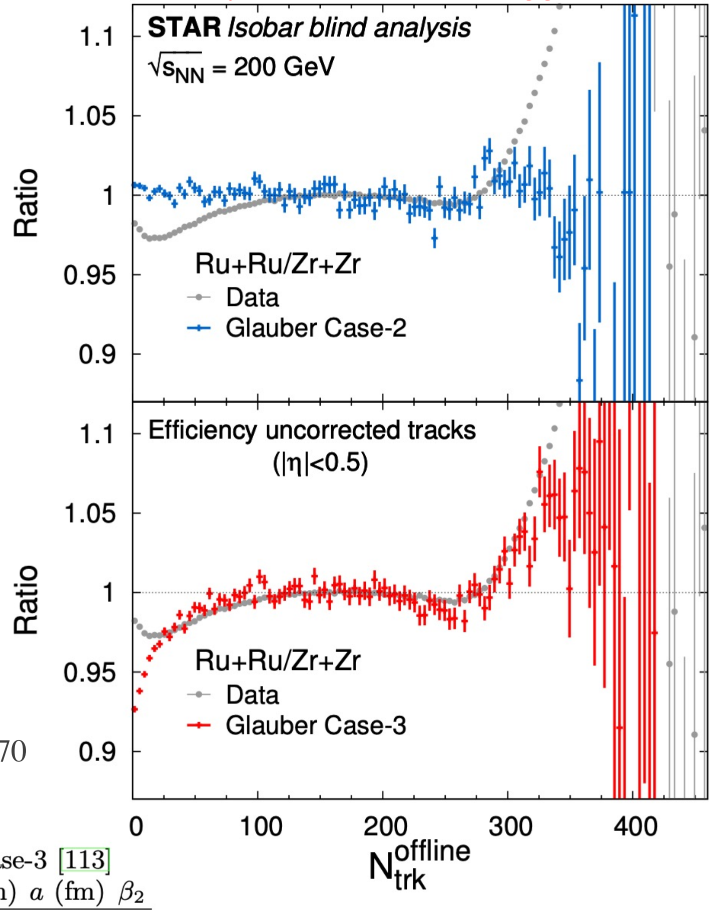
! Note the normalization is very sensitive to the trigger efficiency

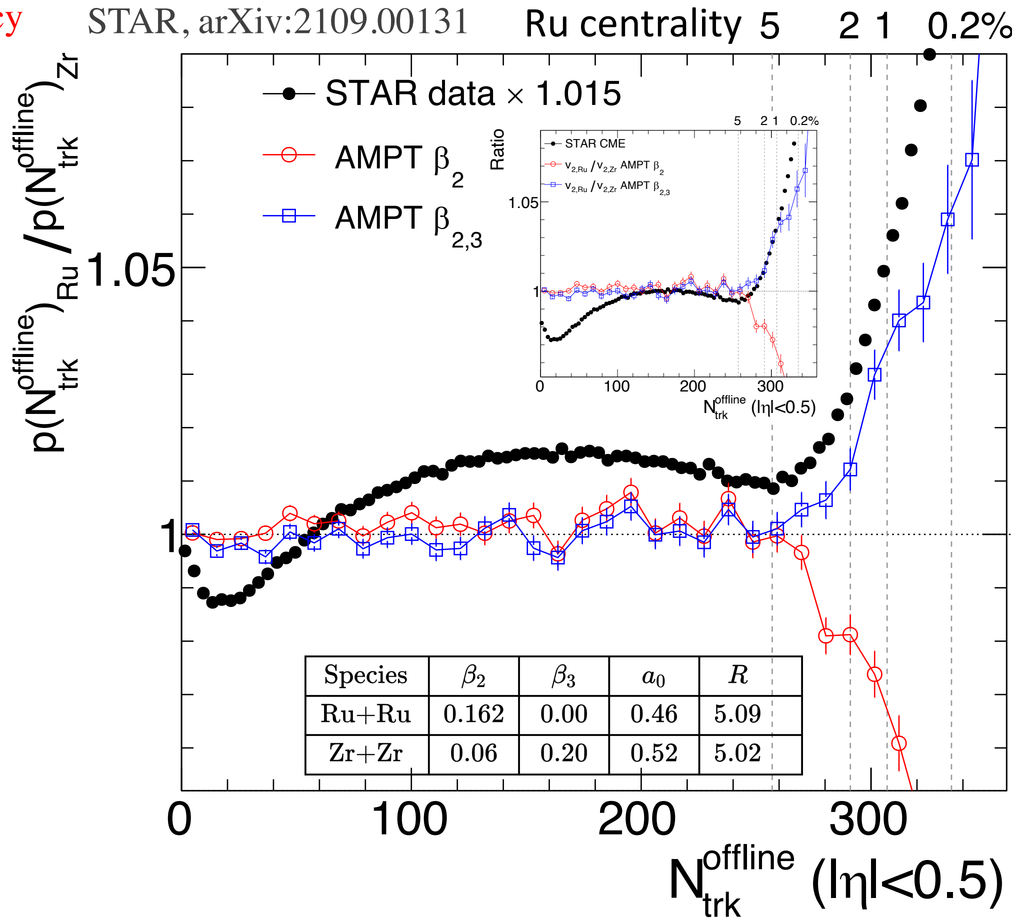
STAR, arXiv:2109.00131



$\beta_2 = 0.162$
$\beta_3 \sim 0$

$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$





STAR, arXiv:2109.00131

H. Xu et al., arXiv:1808.06711, 2103.05595, 1910.06170

Q. Shou et al., arXiv:1409.8375

	Case-1 [83]			Case-2 [83]			Case-3 [113]		
Nucleus	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.02	0.46	0.08	5.02	0.46	0.217	4.965	0.556	0

1) Nonmonotonic trend: bump in mid-central and increase in central

2) When only consider β_2 in case-1 and case-2: constant in peripheral and mid-central, but decrease in central.

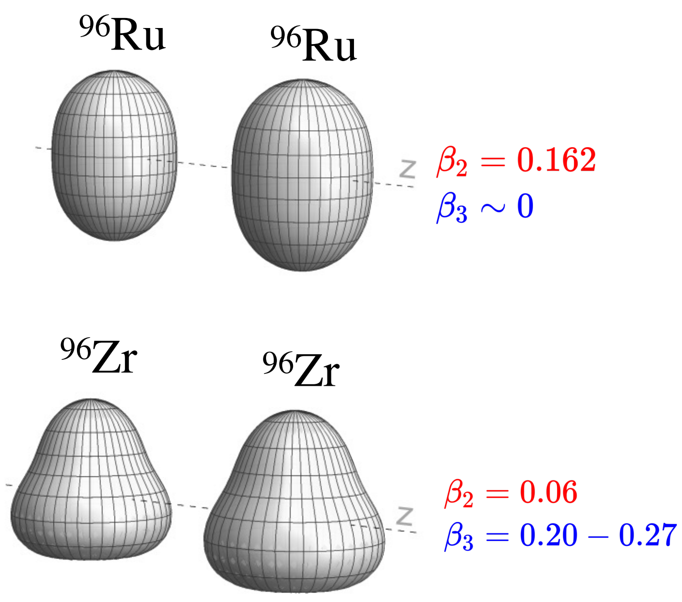
3) But if you consider β_3 in Zr: also can almost get the same tail as Case-3.

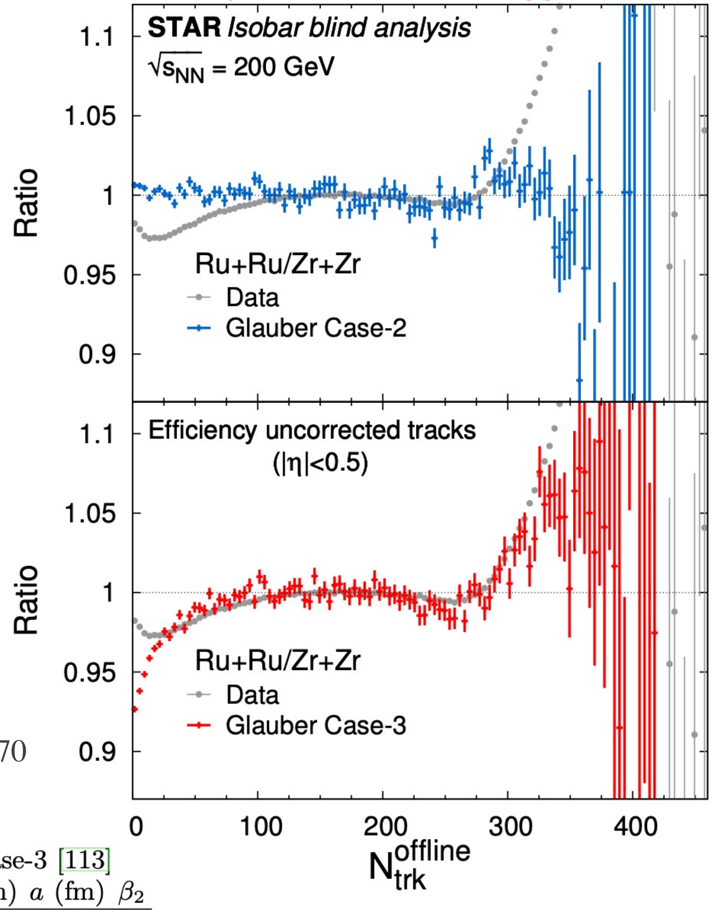
Multiplicity ratio

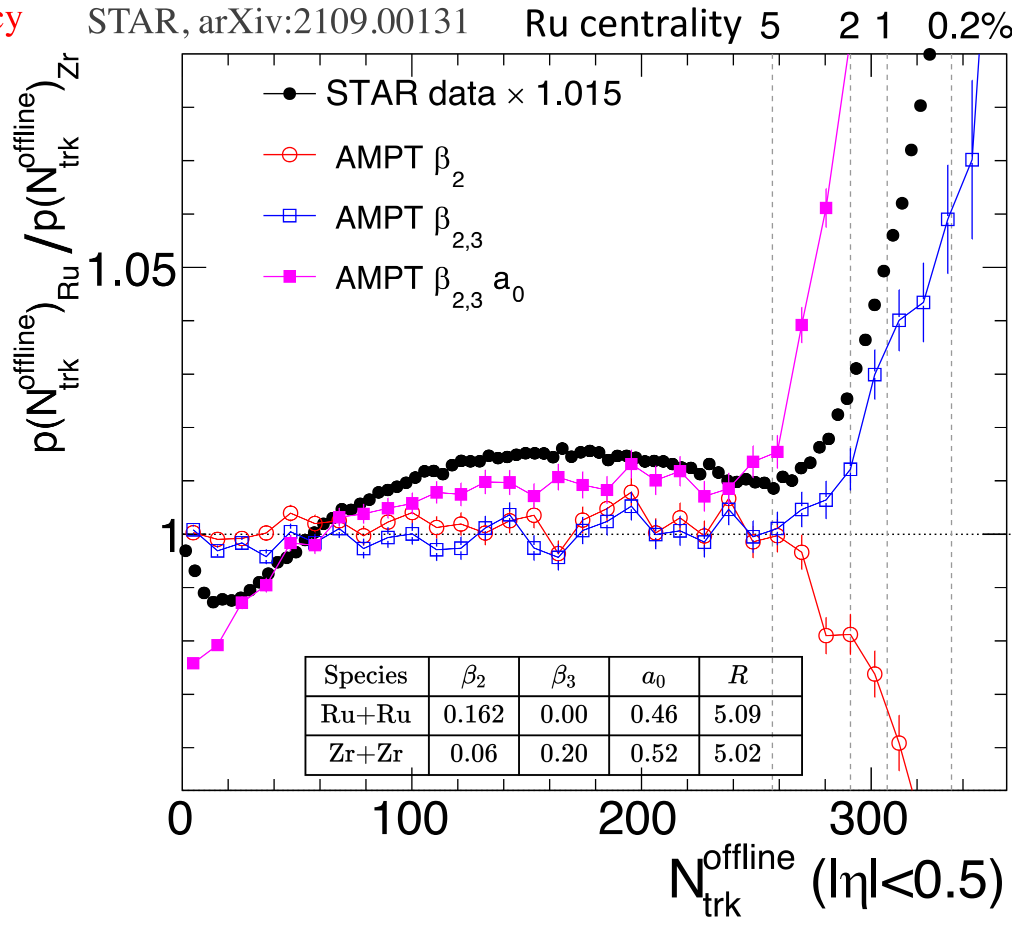
J. Jia, aXiv:2106.08768

! Note the normalization is very sensitive to the trigger efficiency

STAR, arXiv:2109.00131







STAR, arXiv:2109.00131

H. Xu et al., arXiv:1808.06711, 2103.05595, 1910.06170

Q. Shou et al., arXiv:1409.8375

Nucleus	Case-1 [83] R (fm)	a (fm)	β_2	Case-2 [83] R (fm)	a (fm)	β_2	Case-3 [113] R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.02	0.46	0.08	5.02	0.46	0.217	4.965	0.556	0

1) Nonmonotonic trend: bump in mid-central and increase in central

2) When only consider β_2 in case-1 and case-2: constant in peripheral and mid-central, but decrease in central.

3) But if you consider β_3 in Zr: also can almost get the same tail as Case-3.

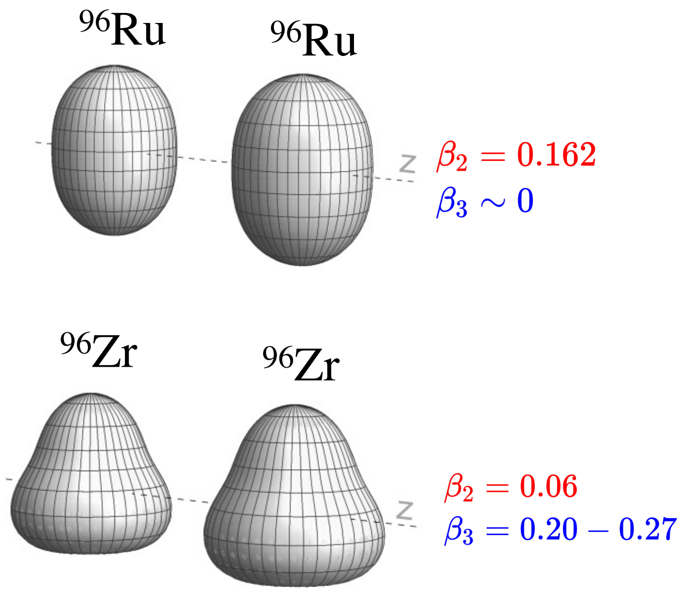
4) Neutron skin a_0 dominates the bump in peripheral and mid-central. But the central tail is more tricky (be careful!).

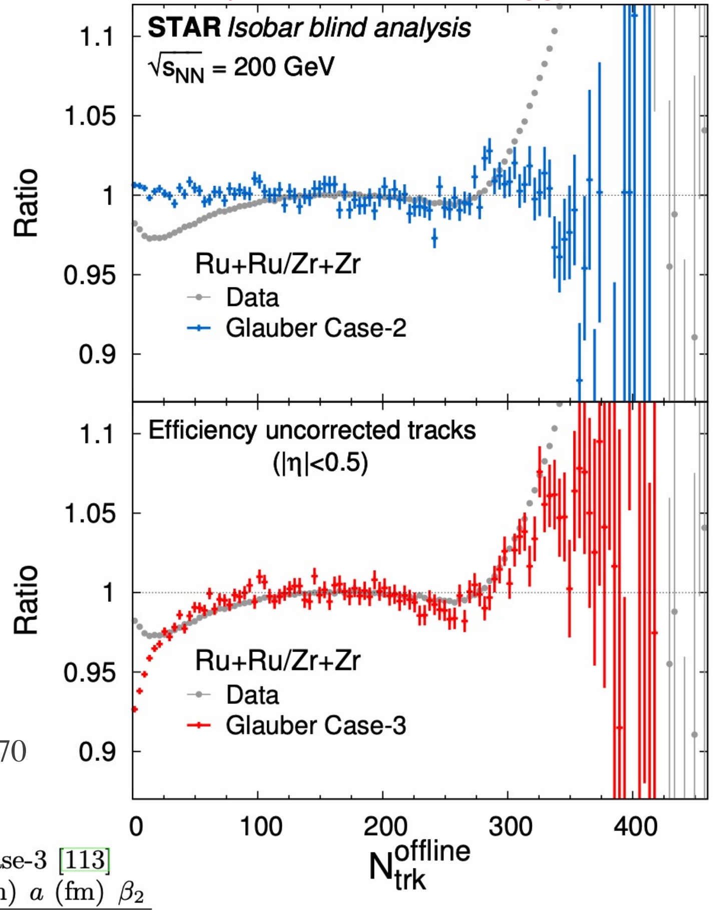
Multiplicity ratio

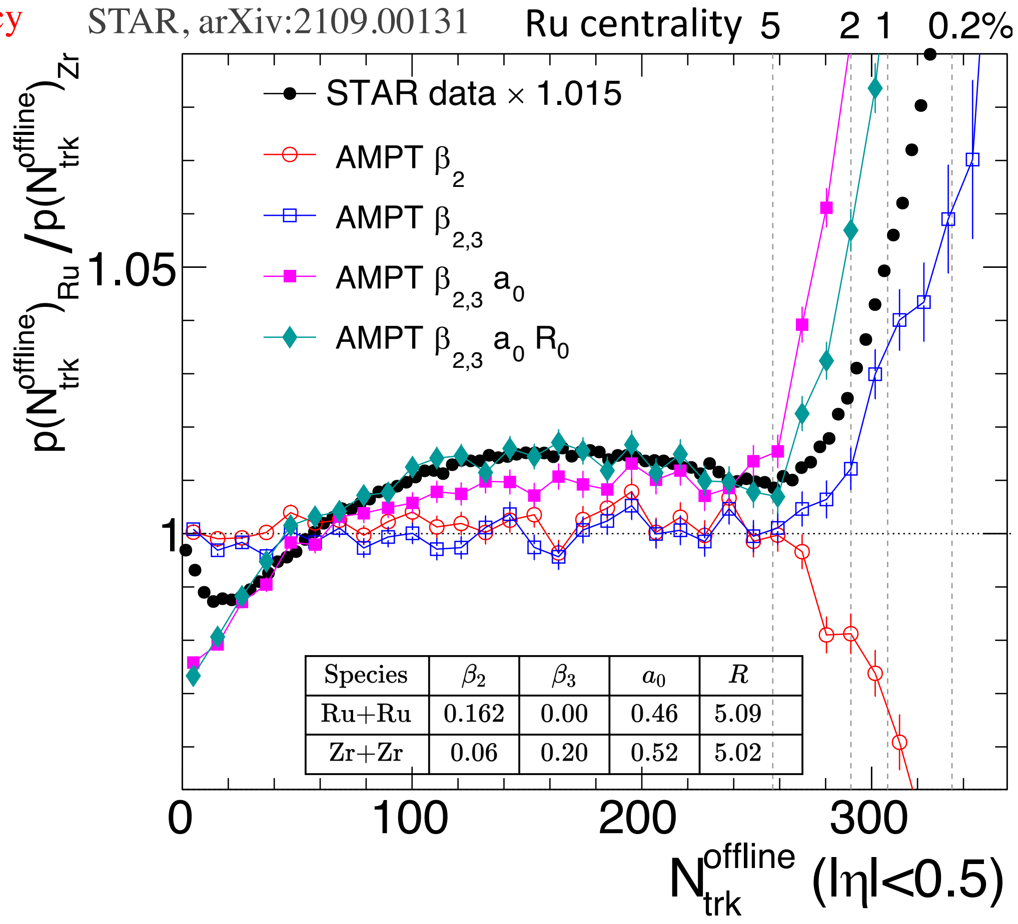
J. Jia, aXiv:2106.08768

! Note the normalization is very sensitive to the trigger efficiency

STAR, arXiv:2109.00131







STAR, arXiv:2109.00131

H. Xu et al., arXiv:1808.06711, 2103.05595, 1910.06170

Q. Shou et al., arXiv:1409.8375

	Case-1 [83]			Case-2 [83]			Case-3 [113]		
Nucleus	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.02	0.46	0.08	5.02	0.46	0.217	4.965	0.556	0

1) Nonmonotonic trend: bump in mid-central and increase in central

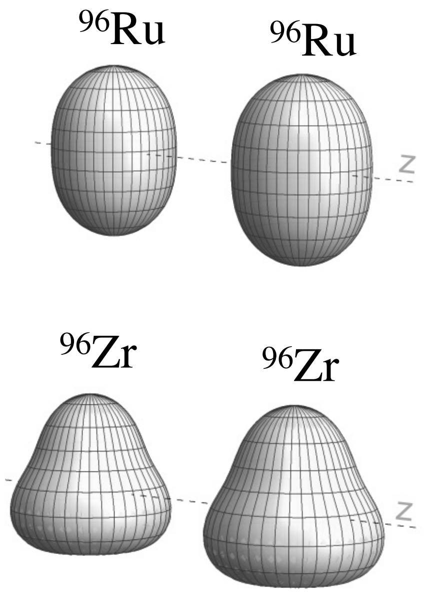
2) When only consider β_2 in case-1 and case-2: constant in peripheral and mid-central, but decrease in central.

3) But if you consider β_3 in Zr: also can almost get the same tail as Case-3.

4) Neutron skin a_0 dominates the bump in peripheral and mid-central. But the central tail is more tricky (be careful!).

5) Nuclear size R also can affect the trend.

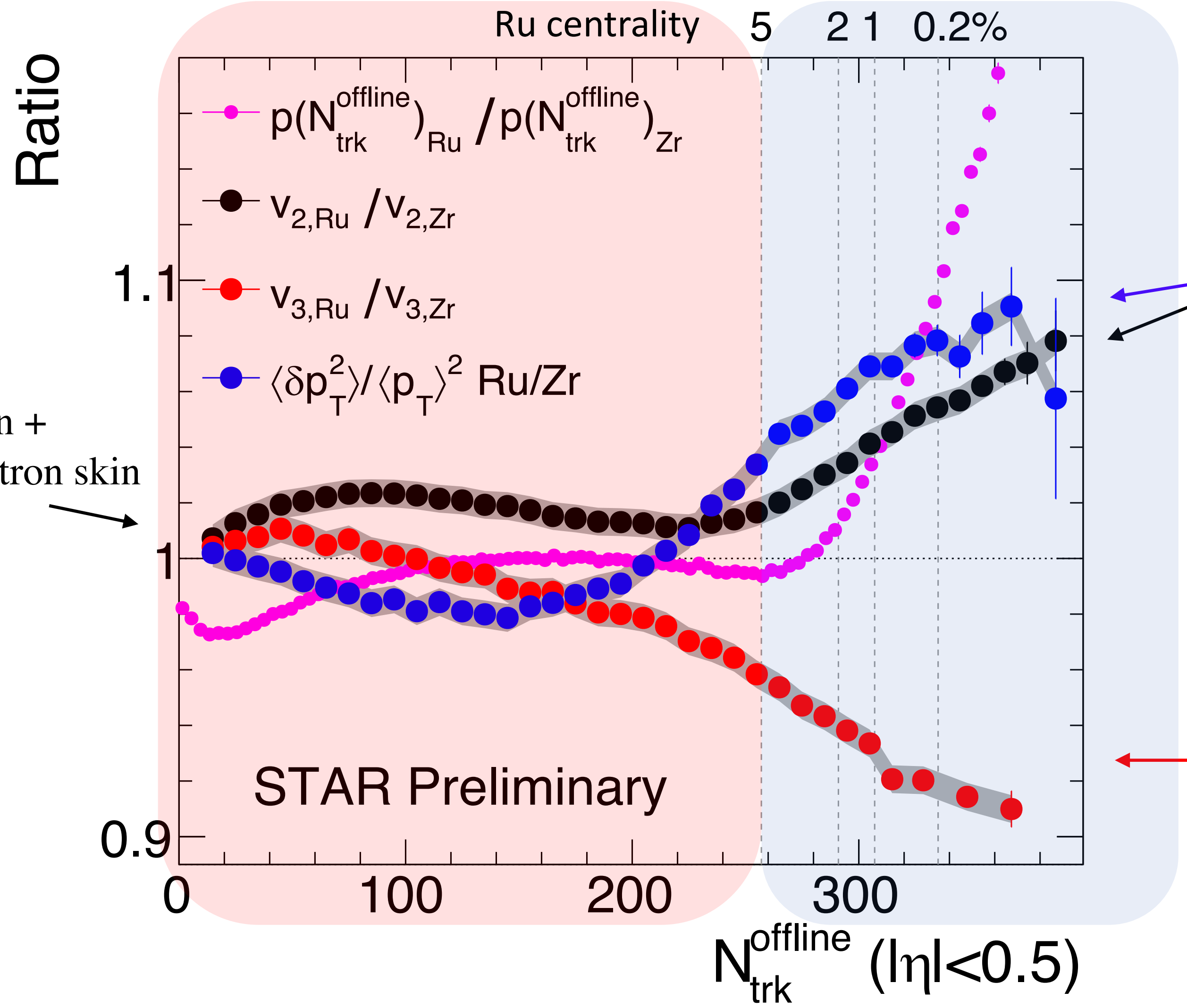
flow, $[p_T]$-variance and multiplicity ratio



$\beta_2 = 0.162$
$\beta_3 \sim 0$

$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$

Nuclear deformation +
Radial structure, e.g., neutron skin



Large $\beta_{2,Ru}$

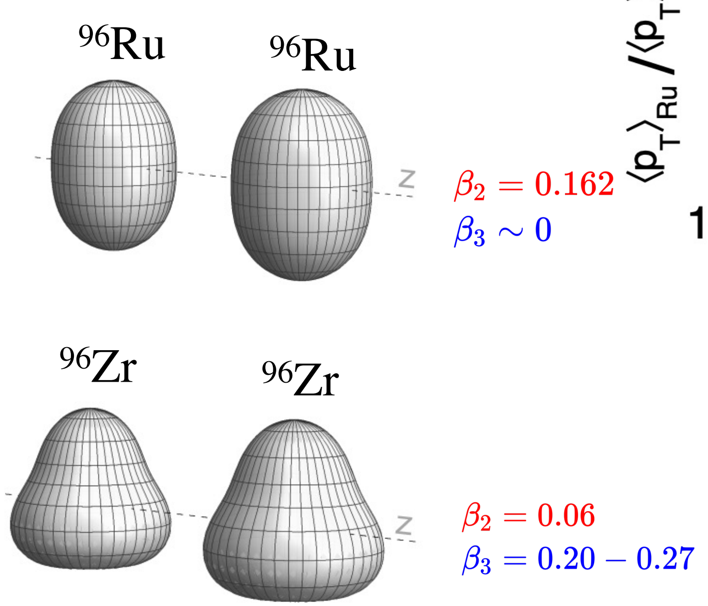
Large $\beta_{3,Zr}$

J. Jia, aXiv:2106.08768
STAR, arXiv:2109.00131
H. Xu et al., arXiv:1808.06711, 2103.05595, 1910.06170
Q. Shou et al., arXiv:1409.8375
C. Zhang et al., arXiv:2109.01631
G. Giacalone et al., 2105.01638

Ratio of any bulk observables can image the shape of the nuclei.

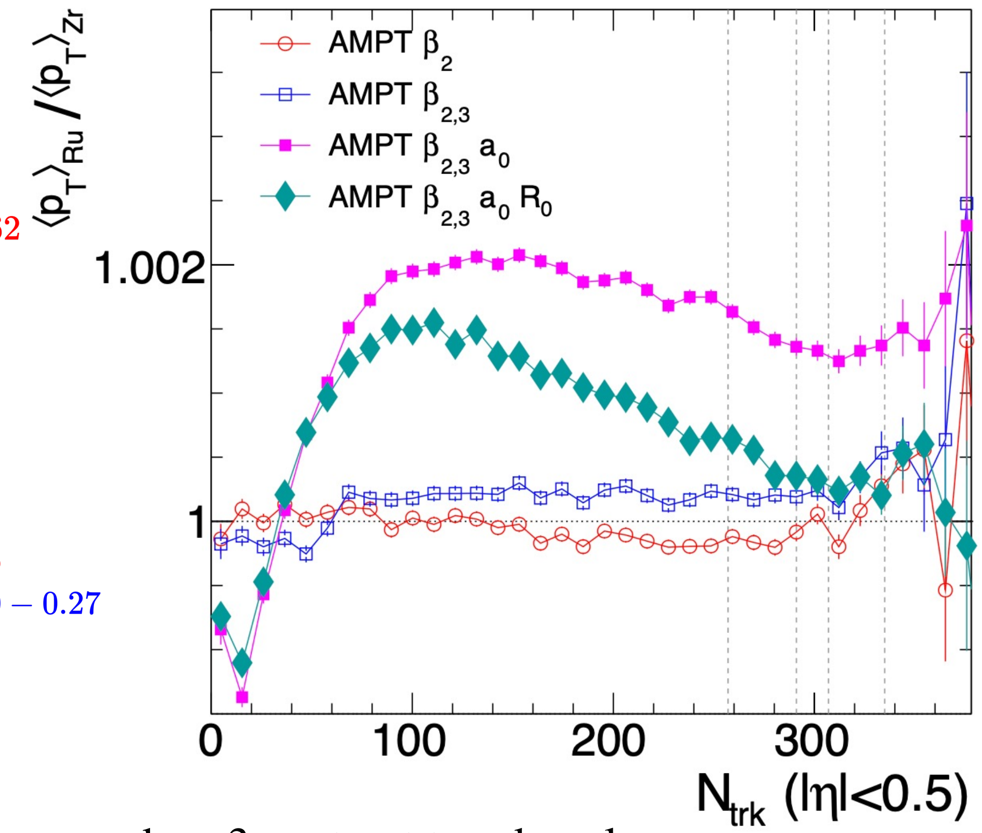
New proposed observable: Nuclear structure via $\langle p_T \rangle$

Jiangyong Jia and Chunjian Zhang, In preparation

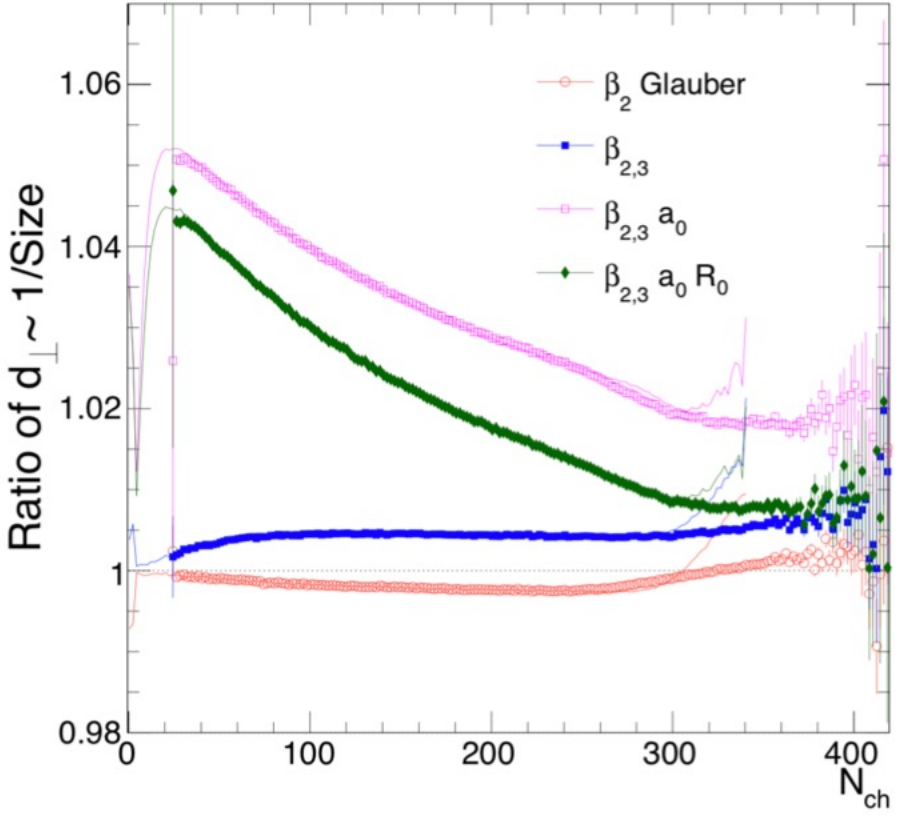


J. Jia, aXiv:2106.08768

AMPT predictions



Glauber predictions



1) AMPT underestimate response by x3, so trust trends only.
2) β_2, β_3 small impact in noncentral, but some increase in UCC
3) Enhancement dominated by surface diffuseness

4) Radius difference leads to stronger N_{ch} dependence
5) Glauber model also describe the trends.

Ratio of $\langle p_T \rangle_{Ru/Zr}$ also could reflect the nuclear structure.

Conclusions and outlooks

- ✓ **Isobar collisions are a new tool to study the nuclear structure.**

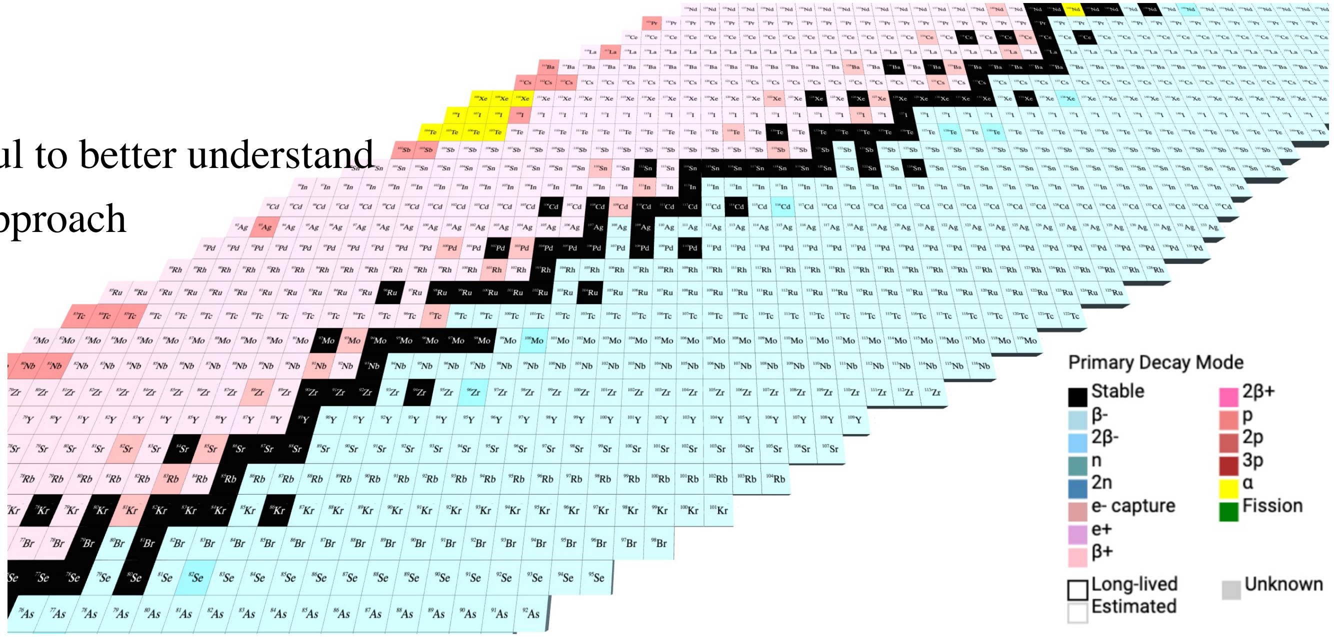
- ✓ **The ratios of v_2, v_3, $\langle \delta p_T^2 \rangle$ and multiplicity have large deviation from one implying:**

  $\beta_{2,\mathrm{Ru}} \gg \beta_{2,\mathrm{Zr}}$, $\beta_{3,\mathrm{Ru}} \ll \beta_{3,\mathrm{Zr}}$, and radial structure, e.g., neutron skin in ^{96}Zr

- ✓ **This is the direct observation of ^{96}Zr octupole deformation/collectivity using heavy-ion collisions.**

- ✓ **Isobar collisions open up new opportunity to study nuclear structure at a very short time scale ($\sim 10^{-24}$s) through heavy-ion collisions**

  - By doing future deformed-system scan
  - Species with well known deformation will be useful to better understand the systematics and establish the efficacy of this approach



Many thanks to ATHIC conference and also thank you for listening.